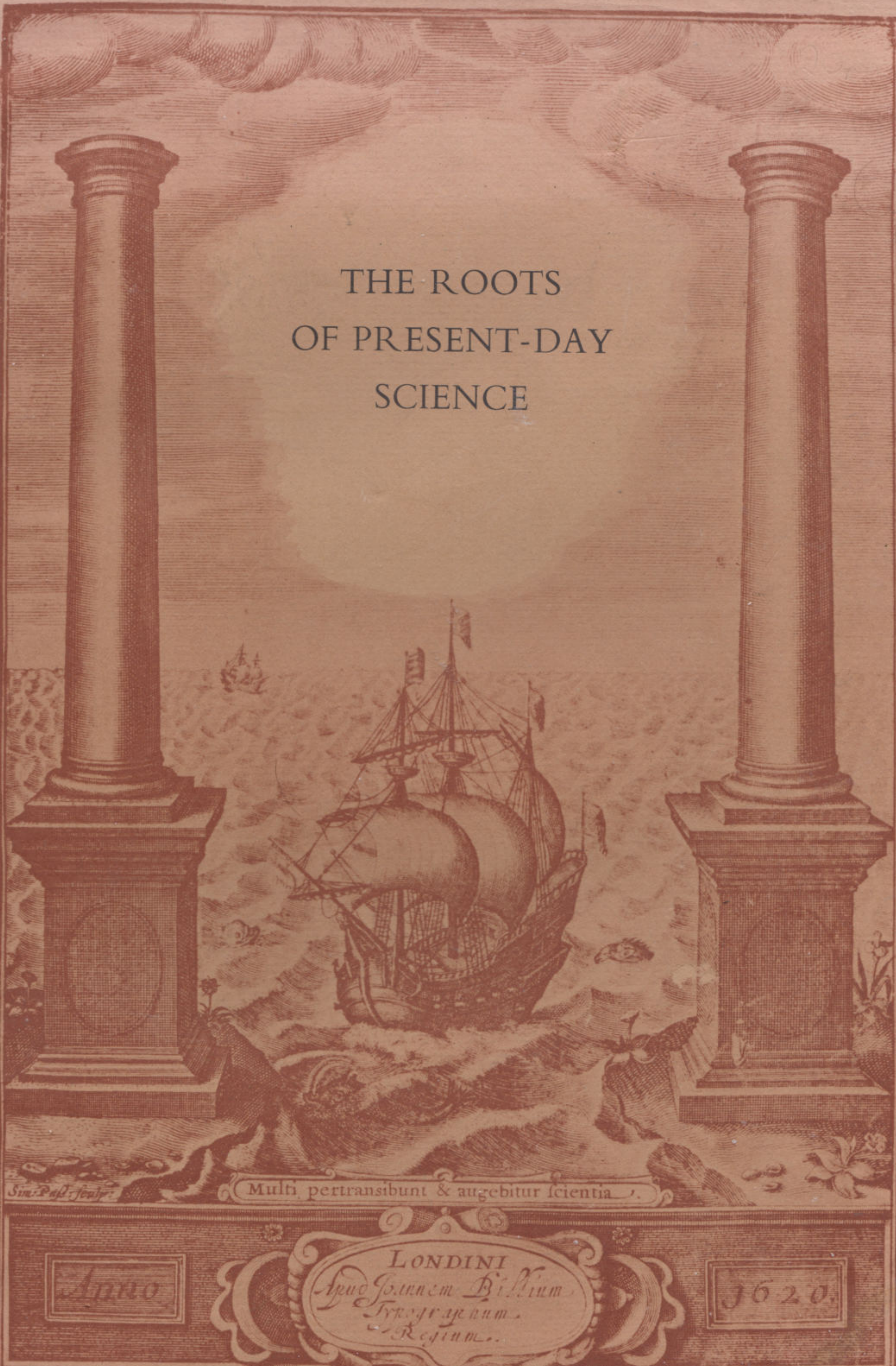
THE ROOTS OF PRESENT-DAY SCIENCE



THE ROOTS OF PRESENT-DAY SCIENCE

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Preface

THIS BRIEF ESSAY ON THE HISTORY OF SCIENCE is rather different in intention from the other material you have received in this Foundation Course. As you will know from the Units you have already read, the written course material presents science with a somewhat timeless quality. We have concentrated on giving you a modern account of where science stands now, avoiding the approach often taken by 'orthodox' science textbooks, namely, to provide a history, or more often a sort of chronology, of the development of certain scientific ideas. Instead, we asked Dr. Ravetz to provide this historical perspective. But we wanted a rather different sort of history from that found in many conventional textbooks. In them, the history of science is often shown as the activity of a series of great men, working in isolation from society and unaffected by the swirling social and political currents of their time. This essay is intended to redress the balance, showing how the intellectual development of science – the gradual establishment of the ordered, rational and interlocking vision of the world which forms the main substance of our Foundation Course – has been affected by these social currents, and has in its turn affected them, throughout its history.

These considerations led us to ask Dr. Ravetz to do a rather unusual job for an historian and philosopher of science: to write his history backwards, starting with the present state of science, and then exploring its historical roots. You might guess why we did this if we remind you that the theme of one of the earth science Units is: 'the present is the key to the past'. We felt this applied to the history of all science, but the reverse is also true, for, to understand today's science and its problems, you must understand its past. Of course, in so brief an essay, it is only possible to hint at many aspects of the history of science; any selection must seem arbitrary, and many conclusions must be stated without the supporting evidence on which they are based. But a short essay has the advantage of giving a clear view of the historical sweep of science. If you want to go into any of the points made here at greater depth, you will need to look at a longer history of science, such as the book by J. D. Bernal, *Science in History*, recommended as background reading for this course. In terms with which you will be familiar, this essay forms a type of 'red-page appendix' to that book.

This essay 'takes off' from Unit 1 and describes a sort of parabola, bridging the course and rejoining it at Unit 33. However, it is a bridge based firmly on the course material, to which you will find references throughout the text. There are also links out to this essay from the main course material.

Unlike that material, however, there are no lists of objectives, self-assessment tests, etc. associated with this essay. It does not represent 'examinable material' for you, in the sense that such objectives might imply. Rather, it is intended to be read in parallel with the course, as an enrichment to it. We are assuming that you will have completed reading it by the time you start work on Unit 33, because it is at that point that main text and historical essay join up once more for the final Units on science and society today.

1. INTRODUCTION

Unit 1 has shown how the work of science proceeds by an extension and refinement of the ordinary human activities of observation and measurement. Similarly, scientific reasoning is a disciplined use of common sense. It is clear that scientific methods can provide a more precise description of the world, but science does far more than that. It provides a deep *knowledge* of the natural world, so that we can understand natural processes that cannot be perceived by the unaided senses and that can be grasped only with difficulty by our common sense. Science has also given us great *power* over the natural world, so that we can manipulate it, gaining a degree of convenience, comfort and security unknown at any time in previous human history.

With the 'Galileo experiment', we tried to give you some idea of the way that science proceeds. But you saw at the end of Unit 1 that even Galileo made an error in the interpretation of his experiment (if you do not remember, refer back to Unit 1, p. 38).

Unit 1 uses this example to show that the achievement and consolidation of scientific knowledge is not a task for any single individual. It is a *social* process, involving the co-operative labours of many individuals, extending through time. Hence, if you are to understand how science came to its present state of great knowledge and power, and at the same time how this has raised new problems and, indeed, dangers, you must study not only the methods of science, but also the men who used those methods and the society in which they were developed – a point which is dealt with in Units 33 and 34.

These new problems and dangers of science and of its applications are now recognized as the main points at which an 'understanding of science' is relevant to human affairs. This is a very sudden shift in the 'common sense of science'. Until quite recently, it seemed that scientific *knowledge* and the methods of its achievement were a major part of human progress, liberating the mind from dogma and superstition in the study of nature and of man himself. But within living memory the new *power* of science has posed such threats that the older belief that science could transform the world to the advantage of Man has almost been forgotten. These new problems will be discussed at the end of this Foundation Course; in a sense the entire course leads up to them.

In order to understand these problems properly, you will need a grasp of the relevant scientific knowledge; hence the Course concentrates on the scientific materials themselves, and discusses their relevance to contemporary problems whenever appropriate. Furthermore, these new problems are 'social' as much as 'scientific'. To understand them you must know something of the ways in which science and society interact. This is an extremely complex process; no obvious law or organizational chart exists for its full description. The present situation has developed in a fairly haphazard way and in response to developments within science, technology and society. You saw at the beginning of Unit 1 that there are several very different senses in which the term 'science' is used:

(i) as the attempt to discover and explain the workings of the world of nature;
(ii) as the application of certain rules of procedure and enquiry;
(iii) as the social institutions within which these activities are carried out;
(iv) as including the whole field of research and development, in both science and technology;
(v) as excluding technological developments and embracing instead only pure scientific enquiry, typically conducted in certain types of institution such as the university or basic research institute.

One way of sorting out this confusion is to analyse the roots of the present situation, as it developed out of the past. By studying the *recent* past, you will discover the different strands of experience from which today's 'common sense' of science has been drawn. And by continuing an exploration into the past, you will see more of the variety of ways in which science and its relations with society have been organized. You will also learn something of the context in which great discoveries have been made, and to appreciate the subtle interplay of factors (not all of them within 'science') which led to the setting of the problems attempted by particular scientists and their solutions. Moreover, you will be able to see by example that

science has had its failures as well as its successes, its periods of decline as well as of brilliance. Thus you will, in general, develop a broader understanding of the work of science as a human endeavour.

The history that we will provide here will be unorthodox in several ways. First, as you will soon see, we shall start from the present, and then consider successively earlier periods. This imposes some difficulties, for the teacher as well as for the student. We are forced to make rigid divisions into 'periods' and in our narrative we jump from the end of one period to the beginning of the previous one. But for the purposes of this narrative we hope that this scheme will be useful.

A second feature of this history is that it is inevitably synoptic; parts of it are treated more sketchily than others, if only because we have not wanted to make this parallel reading overlong. Not everyone's favourite scientist or topic has received a mention. To some degree, we will make up for this selectivity by exploring some topics in greater depth in the radio programmes of the course – the changing concepts of the atom, and the emergence of cell theory, for example.

A third feature is that we attempt to present in this history something different from a mere chronology of events. We attempt instead a history of science which is in part a history of the changing ideas about science and its relations to society. Such an approach is often called an *externalist* view of science, as opposed to an *internalist* one, which discusses the sequence of scientific ideas and discovery without relation to the environment in which they are made. You may indeed disagree with some of the assumptions and interpretations we have made here. But why not? The history and philosophy of a subject are, more than the subject itself, proper topics for discussion and even disagreement. All too often such discussions are confined to the specialist, however, and the student gets only a smoothly finished product. We have tried to avoid this here.

2. THE SOCIAL ACTIVITY OF SCIENCE

If we were introducing a course on 'science policy', we could start with a chart something like the one reproduced in Figure 1. The area inside the circle represents the activity of research; the knobs on the perimeter indicate the different sorts of institutions that are involved in it, and the ways they affect its course. In this chart, the two main poles of influence are industry (including the State) and the Universities. This describes the situation in the English-speaking world; elsewhere, the Universities are not always strong centres of research. The 'research' itself may be divided into four kinds, from the most 'pure' to the most 'applied', though the different classes are generally not neatly separated. A project may be 'basic' for the man doing the work – he is interested in the result only for its relevance to the special field of study – while at the same time it may be 'basic-objective' to a grant-giving agency, who sees its possible usefulness for industrial application.

As it stands, the chart is not simple; and to fill in the names of the institutions, and their relationships, for the 'science policy' picture for any nation, would be a difficult task. Yet, as it stands, it is still not much more than an 'anatomy' of science: the structures abstracted from their function. To understand the 'physiology' of science – what makes it go in the way that it does – it is necessary to introduce factors that do not fit neatly on an organizational chart: the considerations that influence scientists to choose the problems that they work on, and those that influence the institutions representing society at large to support and foster the sorts of science that they do. We return to these themes in Units 33–34.

Any genuine history of science must discuss these factors if it is to explain the social and philosophical changes that have occurred within science over the centuries and the relations between science and society. The classic conflicts (such as that of Galileo) which have shaped the folklore of science and its own ideology* were precisely about such external pressures on

*By the *ideology* of science, we mean the set of beliefs that are held by scientists themselves regarding what the activity of science is for and about, and how it should be conducted.

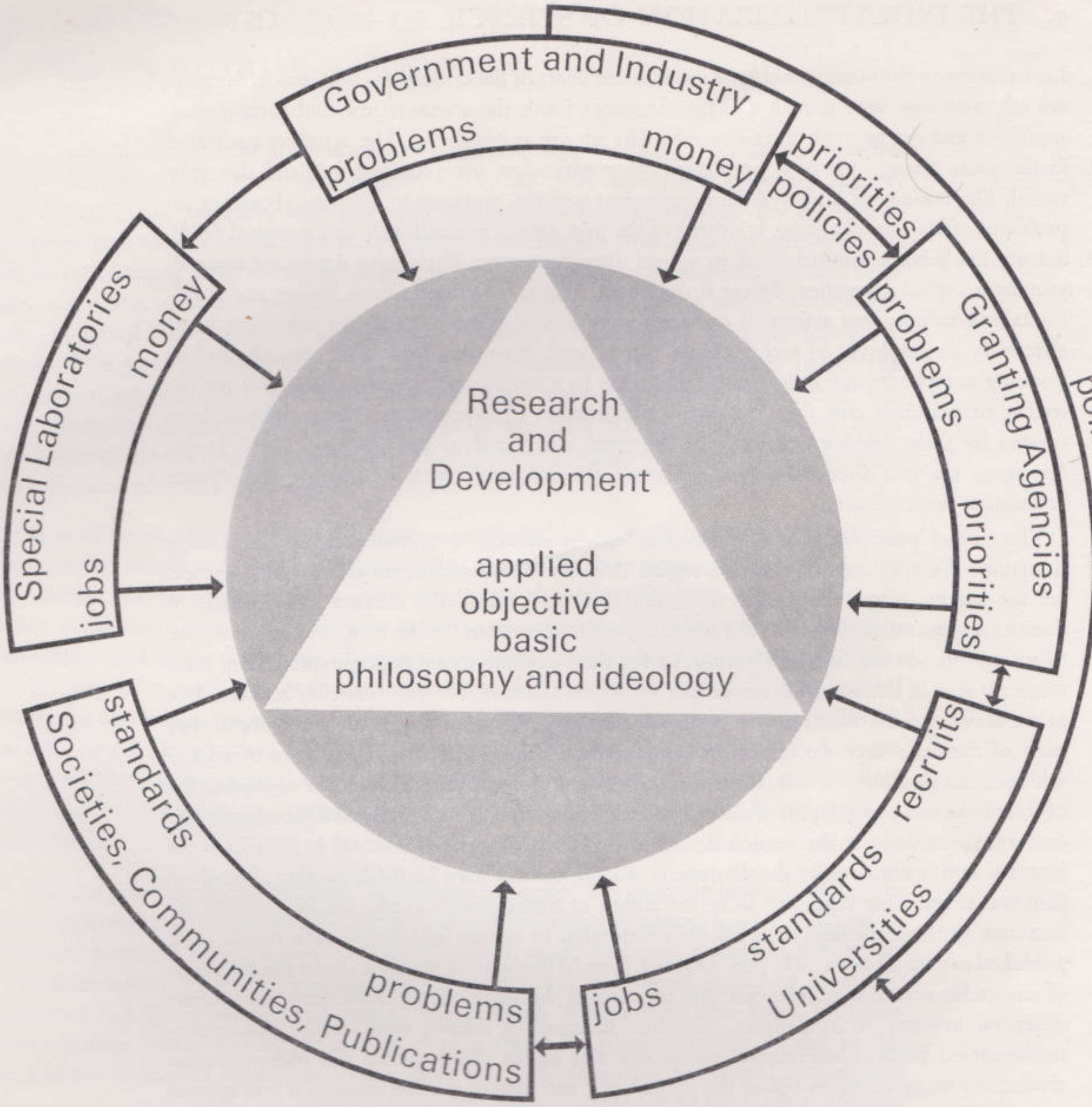

Figure 1 THE INSTITUTIONS OF RESEARCH

science. Finally, we shall see that science has occasionally been caught up in conflicts of ideas related to political struggles between different sections of society; and these too have left their mark.

We can now say a bit more about this unorthodox history of science. As we go back through the various 'periods', we will organize our narrative around the interaction between science and society, as it influenced the dominant style of the period, and also the different sorts of research: philosophical, technical and practical. We will try to indicate the different sorts of contexts and problems that led to the most famous achievements of science, and to tell you about the important failures as well as the successes. From all this, we hope that you will be able to teach yourself to see the present in the perspective of the past, and thereby be better equipped to shape the future.

3. THE INDUSTRIALIZATION OF SCIENCE

Let us return to the present, and look again at our chart of the institutions of research. Suppose we ask ourselves, why is such a chart necessary? Can't the scientists just find their money somehow and get on with their research? The answer is simply no. The activities embraced in the term 'science' are now very large, very expensive, very complicated, and also very useful. The traditional image of the independent scientist, working in his own laboratory on problems of his own choosing, is a thing of the past, except in small-scale and marginal fields. Science has become industrialized, in several important ways. First, most significant research requires a capital investment before it can begin. Hence the scientist is no longer like a self-capitalized independent artisan or craftsman, but is now either a contractor for research, or effectively an employee of such a contractor. Second, the scale of scientific research, and its resulting complexity and cost, require that there be a centralized planning machinery for the setting of priorities and the distribution and control of investments. The social problems created by these developments will be discussed at the end of the course in Units 33–34. For now, we will discuss the third aspect of the industrialization of science – its intimate connection with industry.

The idea of 'pure science' that most of us learn at school is very well defined, and it helps determine the way today's scientists regard new social and ethical problems. Pure science, we are taught, means the pursuit of natural laws concerning the universe, the making of theories and accumulation of results and facts, without concern for the relation they may have to society outside the laboratory walls, or for their possible technological exploitation. Pure science is seen in this model as the proper job of the scientist. The rest is not his concern. But as we shall see soon, this is only a particular ideology of science that is of recent origin. For most of the time since the rebirth of science in the Renaissance, the relationship of science with practice (industry, or war, or medicine) has been unquestioned. Indeed, the strengthening of these links was a central part of the programme of the 'scientific revolution' of the seventeenth century, particularly in the version described by Francis Bacon (1561–1626) in his picture of how a scientific community should operate. Bacon was not only Lord Chancellor of England (and was at one time suggested to be the author of Shakespeare's plays), but he was also the first man to think through in detail the relationship of science and society. His conclusions, published in a major book, *The New Organon*, formed the basis of thought about the functions of science for several hundred years. But for most of this time, science made very little impact either on industry or agriculture. The first successes of science were in the descriptive-mathematical fields; observational astronomy was highly developed in the Mesopotamian civilization many centuries before the present era; and then in the Renaissance it was applied successfully to navigation. Other applied mathematical sciences developed then, such as cartography (map-making), surveying and perspective drawing. Following on this came successes in the science dealing with the simplest properties of matter – mechanics. Galileo's theory of ballistics was useful, if not for cannon, then at least for mortars. The *ideas* of a vacuum and of the pressure of air stimulated research and development through the seventeenth century, culminating in the steam-condensing piston engine of Newcomen. But in this early period, the failures were more noticeable than the successes. Chemistry remained in a state of confusion as an art partly explained by a mystical philosophy. Medicine made little progress right up to the late eighteenth century, in spite of William Harvey's great discovery (1628) of the circulation of the blood.

Only gradually, through the eighteenth century, did physics and chemistry develop the strength and internal coherence necessary if the conclusions about processes that could be studied in the artificially stable and pure conditions of the laboratory (recall the TV programme of Unit 1) were to be applied to the conditions of industrial production. With the coming of the Industrial Revolution, the pace of scientific advance quickened; and we shall see that many of the greatest scientists of this period were deeply involved in industry or war. Even then, the predominant approach was to analyse a craft process and *improve* it, by the use of systematic method and a little elementary science, rather than to *transform* it by the application of laboratory results.

By the middle of the nineteenth century, a new pattern began to emerge: totally new mechanical devices and industrial processes were created by the scaling-up and adapting of scientific discoveries. The first great success in this came in mid-century: the electric telegraph, which obliterated several ingenious systems of semaphores. The successful work here was shared between Britain and America. The next break-through also came in England: the synthesis of an organic dyestuff, by William Henry Perkin (Sr) (1856). At this point in the history of technology, the crucial importance of social factors revealed itself. British industry had developed with the belief that ingenuity and hard work were sufficient, and it was incapable of adapting itself to the conditions of science-based technology. Thus, the beginnings of the economic difficulties found in Britain today occurred long before the Second World War and can be recognized even in this failure of a century ago, which was well understood by some perceptive men, but ignored generally.

The challenge of harnessing science to technological advance was taken up by the Germans, then very conscious of their inferior position as a recently unified, underdeveloped nation. They also had available the scientific manpower to invent new dyestuffs and to break everyone else's patents. By the end of the century Germany dominated the international dyestuff and heavy chemical industries.

The steady transformation of the traditional crafts by science-based industry has continued, at an increasing pace, through the present century. Major firms know that their strength lies not only in their present sales or in their capital equipment but in the products for five or ten years ahead, now being created in their research and development laboratories. The new industries of the twentieth century, such as plastics, telecommunications, pharmaceuticals and motorized transport, have created the material base for our present affluence. Of course, these developments have brought great problems. Advances in war technology help to keep mankind on the brink of extermination; consumer affluence produces vast effluents. But even if we wish to make drastic changes in the concept of technological 'progress' before it chokes us all, it will still be necessary to maintain and develop science-based industries, albeit in a more enlightened and planned way than hitherto, if we are not to abandon civilization altogether.

The establishment of science at the foundations of industry has been a remarkable success story but, at the same time, the status and nature of science have been confused and perhaps compromised. For now, no scientific result can be guaranteed 'pure' and immune from application for good or ill. The most abstract logic can turn out to be crucial for the design of computers. The atomic physicist Lord Rutherford in the 1930s (Unit 6) has been attributed with the remark 'anyone who thinks you can get power from splitting the atom is talking pure moonshine'. Yet his own work was one of the developments upon which the atomic explosions at Hiroshima and Nagasaki in 1945 rested. Since then, no one has been able to be so naive.

4. THE EPOCH OF ACADEMIC SCIENCE

The 'academic' view of 'pure' science has been dominant until so recently that many still tend to take its assumptions as eternal, unquestionable common sense. Its essence is a belief in the value of an intimate relation between scientific research and higher education; that teachers at university level need to do research in order to teach well and, conversely, that scientific research is best pursued within the diversified environment of a university. Associated with this belief is an idea of real science as 'pure' science, a branch of scholarship of the same sort as history, linguistics, or philosophy. We can even speak of an *ideology* of pure science, which conditions a scientist's reactions to the problems raised by the new situation of the industrialization of science. In fact, 'academic science' is a development only slightly older than the beginnings of the industrialization of science. Its origins lie in Germany, in the movements for the growth and improvement of the universities in the early part of the nineteenth century.

Before that time, only in revolutionary Paris could science as an organized social activity

be said to have existed. Those who did scientific research had to depend on private means or on a wealthy patron. There were a few paid jobs in universities or national academies but most of the work was done either by gentlemen, as a cultural pursuit, or by free-lance engineers or physicians, as a sideline. Universities were generally finishing schools for gentlemen, perhaps with special courses for the training of professionals such as lawyers or doctors. Systematic teaching of any sort was the exception, and only in a few good medical and engineering schools was there any instruction or research in science. State support for scientific research was concentrated on technical projects: voyages of geographical and botanical exploration; navigation and its aids; and the development of mining and natural resources. In this social context, the world of science was numerically dominated by amateurs and dilettantes. This was true in Britain, even for a major institution of science such as the Royal Society, founded in 1662, membership of which has subsequently come to signify the recognition of a scientist's merit by his colleagues.

The better German universities had already developed the ideal and the practice of co-operative scholarship – teamwork in research – by the end of the eighteenth century; and early in the nineteenth century, the University of Berlin set an example of excellence in scholarship and teaching which then became the aim of every major city in the German-speaking world. The cultural and industrial benefits following from this development of learning were to bring national greatness in the nineteenth century. The 'arts' subjects were the first to be developed in this way. The scientists, who took their inspiration from the research community that had flourished in Paris in Revolutionary and Napoleonic times (from 1790 to 1815), only more slowly became accepted in the German system as scholars equal to historians and philosophers.

With the growth of university-based research, there developed a system of careers in science and of a community of scientists spread across many centres of work. From this environment sprang the ideal of 'pure' science as an exclusive activity. This can be partly understood in terms of what the idea of pure science *rejected*. Association with industry was considered a contamination of science, whilst involvement with philosophy or broader speculation as to 'the nature of things' was feared as a seductive peril. The scientist was to devote himself to the winning of hard facts about the natural world. If industry could later apply them to human benefit, that was admirable, but none of his personal concern. Similarly, the scientist should want his work to make a contribution to general knowledge and culture, but his own work should be rigorous and close to experience, immune from flights of fancy. This view of science could easily turn into a justification of narrow, over-specialized research, and on occasion did so. Its roots lie in the particular situation of German scientists in their formative period, wanting to join the gentleman-scholars of the Arts faculties of the universities, and yet involved in a long struggle against a brand of philosophy which claimed the interpretation of the facts of the natural world as its province (see section 7 below).

The German ideal of the university as the home of combined teaching and research gradually spread to other nations. It came to America in the 1880s, and to England somewhat later. In these countries where, in the past, research had been considered as one of the permitted eccentricities of a teacher, there then developed something like a profession of men whose task included both teaching and research. The beneficial effect of a university atmosphere on the work of research was recognized; and so, first in Germany and later, in the present century, in Britain and America, research institutions came to be organized within, or in association with, universities.

During the same period, higher technical education was developed, and the conflicts between this sort of education and that related to 'pure scholarship' were worked out in each nation in various ways. We shall see that the model for this technical education came from Paris at the time of the French Revolution. In France, and other countries where the universities remained relatively weak, there have subsequently developed Polytechnics and specialized advanced Technical Colleges which have at least as much prestige and power as the universities. In Germany, the establishment of local 'Technische Hochschulen' (Technical High Schools) took place in parallel to the universities. As technical education developed towards high-level teaching, there was a struggle over its incorporation into the universities themselves.

This eventually failed, and so the 'technical' sector of German higher education remained independent in structure, but heavily influenced by the rigorous and scholarly approach to its subjects that characterized the universities.

In America, the great expansion of universities was in the state-aided, so-called 'land-grant' colleges, which were very practical in their concerns, and it is not surprising that the interpenetration of industry and university science has developed more markedly in America than anywhere else.

In England the nineteenth century saw a complex battle for the development of technical education. The older universities, Oxford and Cambridge, gave no degrees in science, only mathematics. Not only the Mechanics Institutes and such institutions as the British Association for the Advancement of Science, but also several new municipal ('red-brick') universities, owe their birth to the early reluctance of the older universities to accommodate science and the rising surge of demand, from the 1830s on, for a broader and more widely available education. The tensions between 'working-class' and 'upper-class' education, which the battles over science education reflected, are not resolved even today. The British system of the 1970s, with traditional universities and the Open University, Polytechnics and Technical Colleges, still mirrors these conflicts. This is not to say that British scientists as a community were fastidiously 'pure' in the nineteenth century; on the contrary, there is in Britain a strong tradition of science as 'useful knowledge'. Scientists such as Charles Babbage (1729–1871) (Unit 16) were deeply involved in the attempts to spread a scientific education; many others wrote popular texts, lectured at crowded Mechanics Institutes or helped with such ventures as the 'Penny Educator', forerunner of today's correspondence colleges. But the British practice was for each individual scientist to choose his own degree of involvement in industry or society; organized social support for higher education in technology was hampered by the disdain for such things traditional among the British social élite – despite the enthusiasm for science and technology shown by Queen Victoria's husband, Prince Albert.

5. THE ACHIEVEMENTS OF ACADEMIC SCIENCE

In retrospect, we can look back on this period of academic science, extending from the earlier part of the nineteenth century to the middle of the twentieth, as a golden age. Science was continuously expanding and it had gained an institutional setting that fostered growth and success. Scientists knew what they wanted to do, and there was an increasing range of problems to which they could apply scientific techniques with great success. It was only towards the end of this period, well into the twentieth century, that the problems of size, organization and responsibility intruded into the life of science. The foundation of much of the scientific knowledge that is still taught and used comes from this period. The contribution of earlier centuries survives mainly in a few general laws or special instances, like Newton's Laws, Hooke's Law or Boyle's Law (Units 3–5, 22), themselves usually transformed in their theoretical content from their original versions (see Unit 1, section 1.8.1). During the nineteenth century, nearly every existing scientific discipline was transformed, while many others that we now accept as basic were created. Indeed the division of 'subjects', on which undergraduate teaching is still organized (but not in *this* course), comes from this period. Only gradually are the old boundaries now being eroded by new groupings under new names, such as 'physical sciences', 'life sciences', and 'earth sciences'. We shall indicate the greatest achievements in the various fields of nineteenth-century science in order that you can see in detail how complex and variable are the paths of the advancement of science. The first thing to notice is that in this case, as usual, the very greatest men broke the patterns that they helped to establish. The German Helmholtz (1821–1894) is mainly remembered for his statement of the Law of Conservation of Energy, which transformed the physical sciences. But he also did fundamental work in the physiology of perception of sight and sound, which bordered on psychology and on medicine; and his scientific interests derived from a philosophical concern developed in his earliest years. Similarly Rudolph Virchow (1821–1902) is remembered for his development of cell theory (Unit 14), but this was only one event in a career which started in social

medicine, went through social and medical reform, and included anthropology. An even more extreme case is that of Gustav Fechner (1801–1887), who started as an experimental physicist of great distinction, then created 'psycho-physics', and spent most of his later career in somewhat mystical metaphysics.

The general histories of science in this period often tend to underemphasize the philosophical and the practical concerns of the great scientists. Later accounts, which refer to a few results embedded in standard textbook syllabuses, often imply that they were discovered by straightforward 'scientists', so neglecting their rich histories. But if we concentrate on these great men, as we must in such a brief synoptic view as this, we risk the opposite danger – that of neglecting the mass of patient, specialized research which the nineteenth century produced (recall Professor Ziman's account of such 'puzzle-solving' science in the radio programme of Unit 1). It was necessary for the consolidation and growth of the scientific disciplines growing out of it, and its omission is one distortion of history in the account you are reading.

5.1 MATHEMATICS

The progress of science is achieved by the interplay of careful, detailed work and bold conceptual advances. In any history, we inevitably concentrate on the latter, even though this may give a very false picture of what the majority of ordinary and even leading scientists were doing and thought worth doing at the time. Thus, in *mathematics*, the nineteenth century saw the steady advance of knowledge and technique in a great variety of fields, ranging from the most pure to the most applied; yet in retrospect the deepest work was done by a few men, mainly outsiders. For mathematics is a science of concepts. Its roots in everyday experience, although essential to its progress, are tenuous and hidden. Its greatest advances come in new conceptions of the nature of mathematics itself. From earlier times, mathematics had inherited a 'realist' idea of what its business should be. Algebra was 'universal arithmetic' and geometry was the study of certain properties of space. The first effective challenge to this view of mathematics came in the development of systems of 'non-Euclidean geometry'. One such geometry can be represented on the surface of a sphere, where lines are 'great-circles' (on a plane passing through the centre of the sphere), and hence where there are *no* pairs of non-interesting lines. This challenge caused some concern among philosophers in Germany, for the great philosopher Kant had 'proved' that we can have knowledge of space only on the assumption that it is Euclidean. It is significant that C.F. Gauss (1777–1855) 'the prince of mathematicians' had kept his prior discovery of non-Euclidean geometries a secret to himself.

In algebra, a parallel development was initiated by the Frenchman Galois (1811–1832). He had been working on a long-standing problem, that of solving a particularly complex type of equation by means of algebraic operations. By extremely abstract considerations on the structure of the roots of the equation he concluded that it could not be solved. His work was incomprehensible to the masters of mathematics in Paris, and was rejected and ignored; and his politics were considered dangerous by the State authorities, so it was probably at the hands of an *agent-provocateur* that he died in a duel at the age of twenty. Gradually, his ideas penetrated mathematics, and eventually came to fruition in the modern idea of an 'abstract group', a structure defined only by its assigned properties.

Since then mathematics has greatly enlarged and deepened its study of 'abstract' objects, and this sort of mathematics is now sufficiently mature to be applied and to be taught; we see it in the 'new maths' syllabuses in schools, and in the Mathematics Foundation Course at the Open University. But such mathematics depends completely on the rigour of its arguments; there is no direct link with experience whereby a mathematical result can be seen to be 'empirically' useful, in spite of its obscurities in conception or proof. Hence the nineteenth-century achievement in rigour is an essential part of the foundations of the present. The standards of rigour had been laid down in Euclid's *Elements of Geometry*, about 300 B.C., but their extension outside geometry was not achieved until the nineteenth century. The most pressing task then was to bring rigour to the 'calculus', whose logical basis since its invention by Leibniz and Newton at the end of the seventeenth century had been difficult to understand. Bringing rigour to this field involved the banishment of all use of 'the infinite'. The German Weierstrass developed a system of symbols and ideas which are the foundation of rigorous

argument to this day. But the infinite could not be so easily dismissed; and in a very straightforward problem the young Georg Cantor (1845–1918) found himself using construction extending to an 'infinity' of operations, and beyond! From this he was led to his theory of 'transfinite' numbers. He paid a high price for his achievement: the work was viewed with incomprehension and suspicion by leading mathematicians, and eventually he discovered insoluble paradoxes at the heart of his theory. The strain was too great; he had repeated nervous collapses and finally broke down altogether. But his challenge was recognized by the better mathematicians as well as philosophers; from it came the investigations into 'the foundations of mathematics' with which Bertrand Russell (1872–1969) started his career.

5.2 PHYSICS

In physics, links with philosophy, on the one hand, and practice, on the other, were usually present in the work of the greatest men; but the real achievement of the nineteenth century was the creation of a science where before there had been little but speculative philosophy and shallow experiments. The word 'physics' itself received its present definition only during the nineteenth century; before then it had been used in connection with medicine ('physician') or with the study of nature in general. Although there was a continuity with earlier investigations on many topics, the emergence in this period of new tools, together with new social conditions of research, enabled a great acceleration of progress to occur. On the second factor, we may just mention the importance of paid jobs, whereby a man without independent means could now for the first time spend most or all of his time on research. The number of men like this was small at first, particularly in England, and did not increase rapidly. Yet Michael Faraday (1791–1867), for example, was able to secure a post at the Royal Institution, then a recently established lecture theatre and laboratory which became for a while as fashionable as, say, the Institute of Contemporary Arts is today. This eventually gave him time and freedom for his researches.

The new tools were of two sorts: mathematical and experimental. The first came from Fourier's (1768–1830) great achievement in recognizing the general importance of a particular class of equations ('linear partial differential equations') and in creating methods whereby they could be solved and their solutions compared with experimental data. Thenceforth, physics had a powerful language and its arguments were mainly cast in mathematical symbols rather than concrete terms. Physics might have become totally abstract, but for the simultaneous development of instruments and of experimental techniques. With these tools, experimental effects could be produced under controlled conditions, and they could be measured by direct or indirect means.

There had been industries producing precision-instruments for some time previously, mainly concerned with clocks and optical instruments for navigation and surveying. But the increasing complexity of manufacture produced a demand for an increasing range of instruments at a reasonable cost; physicists (and chemists) helped in their development, and also benefited from being able to use them. The drawing-room demonstrations of eighteenth-century 'experimental philosophy' were replaced by laboratory experiments, increasingly specialized, capable of producing the most refined effects under standardized conditions.

The science of electricity shows the various aspects of this development most fully. The phenomena of 'static electricity' (Unit 4) had been known since ancient times; at the end of the sixteenth century, William Gilbert (1544–1603), better known for his work on magnetism, gave an experimental account of it and, during the seventeenth century, philosophers invoked atomic mechanisms to explain, or explain away, this 'occult' (magic) property of matter. More powerful rubbing machines, and the storage instrument of the 'Leyden jar', enabled a closer study of electricity during the eighteenth century. Then the main debate was between a 'one-fluid' or 'two-fluid' theory as the explanation for the phenomena of repulsion; and largely qualitative experiments were used in this debate. A leading participant was Benjamin Franklin (1706–1790), one of the founding fathers of the United States. He also contributed to the applications of science by showing that lightning is merely a gigantic spark; and hence that churches are better protected by lightning-rods than by prayers. His theory was instantly denounced but his practice was soon adopted universally.

Experiments attempting to find a quantitative law of electric attraction were attempted through the century, but all were failures until Coulomb (1738–1806) devised his ingenious apparatus for testing an inverse-square law for electric attraction (Unit 4), and confirmed that it applied. Early in the nineteenth century, Poisson produced the classic mathematical theory of such attractions and the science of static electricity seemed complete.

So it was; but it was by then being swamped by the science of current electricity. The roots of this new science were in the physiology and medicine of the eighteenth century, in which a widespread belief developed that electricity was involved in the action of the nerves, and might be the agency of their 'vital' properties. In experiments on muscle twitches in frogs' legs (see Unit 16) the Italian Galvani (1737–1798) observed small sparks, and his pupil Volta (1745–1827) realized that the sparks were not from the nerves but came from the metal contacts with which the frogs' legs were tied. Volta then produced a 'cell' capable of producing a steady current, and a 'battery' of cells for strengthening it. This new force was little understood, but was applied with great effect in chemistry by Sir Humphry Davy (1778–1829) who used electrolytic decomposition to break down a whole variety of substances, such as the bases (Unit 9), to produce new elements – sodium, potassium, calcium, for example – and to prove that water decomposed into hydrogen and oxygen only.

In the early part of the nineteenth century, these new and exciting electrical phenomena helped spread a wave of speculation about the philosophical bases of matter. One of those attracted by such speculation was a Danish pharmacist, Oersted. Like others, he searched for a connection between electricity and magnetism. He was the first to find it, in the *circular* magnetic field around a current-carrying wire (Unit 4). The French came in quickly; Ampère produced his classic theory of electromagnetism, showing that the two phenomena were complementary. Then there was rapid progress, both in exploring new electro-magnetic phenomena and in refining the methods of production and measurement of current. Even so, the discovery of 'Ohm's Law' of the relationship of current, resistance and voltage, which now may perhaps appear too elementary to be interesting, was plagued by difficulties of experiment (variable current and variable internal resistance of the cells) and of theory (what is the 'force' we now call 'voltage' and indeed, what is the 'current'?). It was only around the mid-nineteenth century that it was firmly established that current is 'charge in motion' (Unit 4). William Thomson (1824–1907) (later Lord Kelvin), who produced the basic equations describing the electric circuit, soon found himself involved as scientist and as entrepreneur in the Atlantic telegraph cable venture; in his case, as for many others, scientific problems and technical problems made different demands, but were not different in principle or in interest.

The later history of electricity involves the use of the principle of conservation of energy (Unit 4) as a guiding principle in theoretical research, and the outstanding achievement of this period was Clerk Maxwell's (1831–1879) formulation of the equations of the *electro-magnetic field* (Units 4 and 28), and his identification of light as electromagnetic radiation. This achievement solved many problems, but raised many more. At this point most accounts of modern physics introduce the 'Michelson-Morley' experiment (Unit 3) which supposedly refuted the theory that light travels in a mechanical medium, the 'aether', and set the problem which Einstein (1879–1955) solved. In fact, this very confused and long-extended series of experiments cannot be interpreted so simply. Einstein himself was led to the theory of relativity primarily by considering some theoretical problems raised by Maxwell's equation.

In the present century, the great increase in knowledge and power that electricity represented has led to another fundamental conceptual advance. Today's complex electrical and electronic circuits may be seen as transferring *energy;* but they may also be seen as conveying *information* in a particular code (Units 16, 18). The latter conception was appreciated by Norbert Wiener (1894–1964), who named and created the science of *cybernetics*. This philosophical achievement led directly to powerful industrial applications in computational machinery, control mechanics and guided missiles. Wiener himself turned to neurophysiology in protest against this use of his science and wrote passionate books reminding the world of its new responsibilities in the face of what he called the 'sorcery' of uncontrolled scientific technology.

The science of heat shows a similar pattern. It was not until the eighteenth century that

'heat', 'temperature' and 'fire' were firmly distinguished. The Scottish physician and chemist Joseph Black (1728–1799) made the basic moves in his discovery of the 'specific heat capacity' characteristic of a material, his method of 'mixtures' to determine that capacity, and his discovery of 'latent heat', which was liberated on freezing and absorbed on melting (Unit 5). Even then, there was no apparent reason why it would be impossible to gather up the latent heat of a freezing substance and concentrate it at a higher temperature. Thus it seemed one could, by freezing water, liberate enough heat to boil a kettle resting in it.

By the beginning of the nineteenth century, partly through problems related to the development of the steam engine, scientists had to cope with a great many phenomena of heat in which there seemed no possibility of unity: radiant heat, heat of friction, heat produced chemically and by the compression of a gas. None of these were 'pure' problems of heat; but heat was seen as an agency fundamental for chemical change, for life on the Earth, and for making things move. There were brilliant false starts: in France, Laplace (1749–1827) developed an ingenious model of a substance of heat, 'caloric', which he imagined as clustering around the particles of matter. Fourier rejected this, and developed his mathematical tools in the context of a study of the flow of heat within solids, without defining its nature. The break was made by an outsider, the son of the great Lazare Carnot, the 'organizer of the victory' of the French Revolution. In the 1820s, someone with such Republican antecedents and sympathies was not a convenient protégé for anyone in the Paris scientific establishment. So Sadi Carnot (1796–1832) wrote his memoir *On the Motive Power of Fire* and died in obscurity a few years later. This was a study of the theory of machines, which made a brilliant synthesis of ideas about the conversion of heat into work, and the measure of its efficiency. The memoir itself was ignored and, even though its contents were later summarized by Carnot's friend Clapeyron (1799–1864) in a well-known journal, it was 'ahead of its time' until the 1840s. Today it forms one of the theoretical underpinnings of the internal combustion engine and is the basis for one approach to the Second Law of Thermodynamics (Unit 5).

The mid-nineteenth century was the time when the concepts of energy and of energy conservation developed. The roots of these ideas are astonishingly varied and complex. First, mechanics itself had to be prepared for the innovation; a group working in 'industrial mechanics' in Paris (Poncelet, Coriolis*) were able to establish the concept of 'work'. It could then be related to Newton's force, which acted on mass by accelerating it. Then, with the detailed study of the different agencies of physical and chemical change, there developed an interest (very marked in England) in the 'correlation' and 'conversion' of the 'forces' of nature. The neglect of Carnot's memoir did not mean that there was no interest in the special conversion of heat into work, and empirical studies and theoretical speculations proceeded.

The first statement of the Law of Conservation of Energy was made in Germany by Robert Mayer (1814–1887), a philosophically minded physician, but his paper was rejected by the leading German physics journal. At the same time, James Joule (1818–1889) was proceeding with characteristic English caution to the difficult task of *measuring* the inputs and outputs of a conversion process; when he got a rig that worked, he was able to announce a constant for a 'mechanical equivalent of heat', an early statement of the First Law of Thermodynamics (Units 4 and 5). This idea contained difficulties quickly seen by William Thomson; if heat was converted to work in an engine, was it simply destroyed if the hot body cooled down without doing work? This problem could be solved only by the introduction of a new concept, involving *availability*, and this, later named 'entropy', was at the heart of the Second Law of Thermodynamics (Unit 5). The first clear and acceptable statement of the First Law of Thermodynamics was made by the polymath Helmholtz (1821–1894), whose background was in medicine, physiology and philosophy. As usual, the first synthesis of the ideas of thermodynamics created a host of new problems, conceptual and technical. Max Planck (Unit 29) came into science when this field seemed ready for sorting out; but years later he found himself forced to introduce an *ad hoc* hypothesis about radiation, which violated all the mechanics and thermodynamics he had tried to establish. This was seized upon by Einstein as the

*The 'Coriolis effect' is discussed in Unit 22.

'quantum principle' and, with it, the physics of the twentieth century was born (Units 6, 29, 30).

By the end of the nineteenth century, physical experimental apparatus, although small and inexpensive by today's standards, was already capable of creating controlled environments with properties very different from those existing without human intervention. For example, the development of vacuum pumps made possible the study of very weak radiations from hot or electrically charged materials. In an ordinary atmosphere, such radiations would be very difficult to produce or detect. Chemistry had developed to the point where minute traces of elements could be isolated from an ore and then analyzed and identified by their chemical properties. With such tools, it was possible for experimentalists first to discover and then to analyse new and strange forms of 'radiation'. Working with 'Crookes tubes', Röntgen (1845–1923) perceived the significance of invisible rays that fogged photographic plates and gave them the name of mystery by which they are still described, 'X-rays' (Units 2, 28). By heroic labours, Marie Curie (1867–1934) isolated the first 'radioactive' elements (in 1898) and then solved the mystery of their varying radioactivities by showing that they were spontaneously transmuting, one to another, in regular chains, at regular rates (Unit 31). Rutherford's school went the deepest of all, bombarding a metallic target with 'α-particles' and finding that, instead of being uniformly deflected, some of them were reflected as if by bouncing off a small heavy centre – the nucleus of the atom (Unit 6).

Younger physicists in the early twentieth century felt themselves to be embarking on a great revolutionary programme: to understand phenomena which were utterly unknown to their seniors and, in order to do this, to invoke principles which seemed to contradict the basic assumptions of physics from Galileo onwards. Bit by bit a theoretical structure was developed, through Bohr's model of the atom, which explained the simplest spectral lines, to de Broglie's fertile insight into the duality of particles and waves, and the mathematical formalisms of Heisenberg and Schrödinger (Units 29 and 30). Their work was often closer in spirit and style to philosophy than physics; in their debates, not only physical arguments were invoked but also considerations of method, of the theory of knowledge, and of the nature of things (Unit 29). Thus was created the 'quantum theory', which, by the 1930s, was approaching maturity.

Parallel to this, and interacting with it, was the development of increasingly powerful apparatus for exploring the atom; and with it knowledge of the energy exchanges in the transmutation of elements. It seemed that mass and energy were interconvertible in certain reactions, by a formula produced by Einstein in his first relativity theory (Unit 3); but Rutherford (1871–1937), in England, for instance, was sure that such a reaction could never be self-sustaining. He was proved wrong by Hahn and Strassman in Germany, on the eve of the terrible conflict with Nazi Germany. Then, in the space of five years, this aristocratic, philosophical field of pure physics became the most gigantic military engineering project ever known. A group of eminent scientists convinced President Roosevelt of the necessity for an atomic bomb as a deterrent against a possible Nazi bomb. It was made; and even after the collapse of Germany, work continued; finally, when the Japanese collapse was already imminent and inevitable, the bomb was used twice against Japanese civilian populations*. The 'atomic age' was born.

5.3 CHEMISTRY

Whether science, taken as a whole, was ever separate from such connexions with industry and war is another question. Indeed, when we pass from physics to other fields, we find that involvement with practice was the rule rather than the exception, even during the 'academic' nineteenth century. Chemistry has a much longer continuous history than physics but, until the nineteenth century, it was more an art than a science, with its theory and practice sharply separated. Its theoretical side was highly speculative, with tendencies to the mystical. Talk of 'elements' and 'active principles' linked the language system of chemistry to that of mediaeval alchemy. Practice grew by way of metallurgy and the accurate use of the balance, serving

*The moral problems this posed for the 'atomic scientists' are discussed in the radio programme of Unit 31.

the chemical industry, on the one hand, and medicine, on the other. During the eighteenth century, theory and practice gradually linked to approach the conditions of a science, with reliable facts from experiment and fairly controlled theorizing.

The endeavour to make a science of chemistry in the eighteenth century included an attempt at a comprehensive theory of chemical reactions, using the empirical idea of 'affinity', explained in terms of Newton's speculative ideas on the short-range forces between atoms. This effort culminated in the work of Berthollet (1748–1822) in France, on 'chemical statics' (1803), which turned out to be an obituary for a century's endeavour. With hindsight, we can see that the more fruitful work in the long run was the steady accumulation of reliable analyses of particular substances, and the development of instruments and reagents. This progress led to a sense of need for reform of chemical nomenclature, especially among the rationally-minded French, and Lavoisier (1743–1794), previously a man of very general scientific and industrial interests, joined the group working on the project. He soon adapted it to his own ends: the reform of chemical *theory*. The folk-histories of chemistry portray Lavoisier as the shining knight who identified the evil dragon that was retarding the progress of the science, namely a thing called 'phlogiston', the fire-principle which is 'lost' by a body on combustion. In its place, the story goes, he substituted truth, in the form of Oxygen, the element which most frequently takes part in an exothermic reaction. The proper history is more interesting, but also more complex; it is sufficient to know that Lavoisier's 'oxygène' was not quite an 'element', but more a *principle:* that of *acidification* (the Germans still call it Sauerstoff) (Unit 9). For he had a vision of a grand unified theory of the elements and their reactions, in which acids are *all* formed by combustion; and this sketch of a theory was built into the successful nomenclature. In spite of these slight flaws, his nomenclature did sort out a mess, and could be adapted easily to new elements and new compounds; and his insistence that there is a large set of different classes of substances was a fundamental advance.

However, Lavoisier's system did not enjoy the period of consolidation and detailed improvement that is customary for a great scientific advance; chemistry was soon to move too quickly for that. The idea of substances as composed of distinct atoms was taken up by a North-country Quaker schoolmaster and experimental philosopher, mainly interested in meteorology, as befitted his upbringing in the Lake District. John Dalton (Unit 6) started with problems of the mixture of gases (why don't the heavier components of the air settle at the bottom?) and the solubility of liquids in gases. His researches led him to a rather crude model of gases as composed of atoms surrounded by 'puff-balls' of heat; and at a certain crucial point he passed from considering their physical mixture to their chemical combination. Using a convenient selection of data on the weights of constituents of chemical combinations, he perceived the Law of Multiple Proportions and interpreted it as indicating the grouping together in clumps of individual atoms of each substance. As his theory was presented to the world of chemistry, difficulties and anomalies abounded; but chemists soon found that, while they could not take it too literally, they could not do without it. Nevertheless, the resistance to speaking of the unobservable 'atoms' lasted through the nineteenth century and relics of this are still to be found in some elementary courses in chemistry.

With these two powerful, albeit imperfect, organizing principles, and a host of new phenomena created by the application of current electricity, chemists in the early nineteenth century engaged on the task of making a science out of an art. Only the leading conceptual advances are mentioned here, for the amount of detailed experimental work on which they depended fills many volumes. For a long time, chemists studying the simple reactions were so near and yet so far from comprehension. Constituents of a reaction could be weighed by increasingly refined techniques and, from a comparison of 'combining weights', one could hope to see how much (or how many atoms) of each substance was involved. But the circle could never be closed; no-one could ever be sure which basic reaction involved a single atom on each side. In a nutshell, it reduced to this: is the formula for water HO or H_2O? Combining weights tended to one set of answers, and combining volumes to another. The riddle is solved when we know that, for instance, oxygen gas has two atoms in each molecule.

On the theoretical side of chemistry, progress was slow. The massive and painstaking contributions of men like Berzelius included analyses of materials of all kinds so that, for the

DATE	CONTEMPORARY HISTORY	SCIENCE, SOCIETY AND CONTEMPORARY THOUGHT	TECHNOLOGY	MATHEMATICS
500 BC to 1400 AD	classical to mediaeval times rise of Christianity and Islam	science linked to mathematics, philosophy and religion age of folklore, magic and mysticism growth of astrology and alchemy, and rise of mathematical astronomy	metals, glass astronomical instruments clocks, gunpowder, magnetic compass	*Pythagoras* number, physical laws *Euclid* geometry introduction of arabic numbers
1400	Renaissance mercantilism	rediscovery of	development printing of	
1500	voyages of exploration	classical writers	navigation	
	Reformation		microscope	*Cardano* algebra *Stevin* decimal notation
1600			telescope	
		Bacon 'The New Atlantis'		*Descartes* algebra, geometry
1650		*Descartes* mechanical philosophy		
	rise of scientific academies	founding of Royal Society (London) French Academy of Science		*Newton, Leibniz* calculus
			Savery steam pump	
1700				
	'Age of Prose and Reason'		*Newcomen* steam engine	
1720				
		Voltaire the Enlightenment		
1740				*Euler, d'Alembert* partial differential equations
			Agrarian Revolution *Harrison* marine chronometer	
1760		Romanticism	*Roebuck* Carron iron works *Boulton* metal factory *Hargreaves* spinning machinery *Arkwright*	
		Rousseau 'the social contract' *Kant* 'Critique of Pure Reason'	*Crompton* *Watt* rotary engine	
1780			*Cartwright* power loom	*Fourier* series
	French Revolution	*Adam Smith* 'The Wealth of Nations' *Paine* 'The Age of Reason'	*Jenner* vaccination	
1800		Ecole Polytechnique (Paris) *Malthus* on population	*Trevithick* high pressure engine *Bramah* machine tools *Maudslay* *Whitworth*	
1820		beginnings of laboratory training		*Cauchy* complex variables
	free trade	German 'Naturphilosophie' *Goethe* *Bentham, Mill* Utilitarianism	*Stephenson* locomotive telegraph *Chadwick* public health	*Galois* group theory
1840		growth of universities		
		Darwin 'The Origin of Species'	*Bessemer* cast steel	
1860	growth of industry		internal combustion engine	*Weierstrass* rigour in analysis
	British Empire at height	*Marx* 'Das Kapital' development of science in American universities	*Lister* antiseptic surgery	
1880			*Edison* power station	
		Germany dominates chemical industries		
1900			radio *Wright* aeroplane mass production of cars	*Russell* new mathematics
	World War I Russian Revolution			*Hilbert* abstract mathematics
1920			television nylon plastics catalytic cracking of crude oil	
	World War II		radar sulphur drugs	
1940	national independence of colonial people rise of the 'Third World'	social responsibility of science	electronic computers missiles atom bomb hydrogen bomb	
1960		science and the environment	space technology guided missiles anti-missile- chemical and missiles biological warfare	
		military-industrial-scientific complex		
1980+	mass destruction or social transformation	retreat from rationality, *or* science for the people	population explosion, doomsday weapons, computerized society, genetic engineering, pollution *or* fertilizing the Sahara, massive agricultural programmes, world without want	

PHYSICS	CHEMISTRY	BIOCHEMISTRY	BIOLOGY	EARTH SCIENCES
Democritus atom *Ptolemy* descriptive astronomy *Aristotle* reason, logic *Plato* idealism *Socrates* dialectic			*Galen* medicine, physiology *Avicenna* medicine and physics	
Copernicus solar system	*Paracelsus* iatro-chemistry *Agricola* metallurgy		*Leonardo da Vinci* anatomy, natural history, mechanics *Vesalius* anatomy	
Gilbert De Magnete *Galileo* mechanics *Kepler* planetary orbits			*Harvey* circulation of the blood	
Boyle, Hooke, Mayow breathing and combustion *Boyle* gas law *Hooke* experimental physics *Newton* laws of motion *Romer* velocity of light *Huygens* wave theory				
			Linnaeus classification	
Leyden jar *Franklin* static electricity	*Scheele* discovery of chlorine *Becher, Stahl* phlogiston theory			
Black latent and specific heat	*Priestley* discovery of oxygen *Biringuccio* 'Pyrotechnia' *Lavoisier* proposed alternative to phlogiston theory, physiology of respiration			
Coulomb law *Galvani* current electricity				*Hutton* theory of the Earth *Werner* cataclysms
Volta battery *Fresnel* wave optics *Boscovitch* matter and force	*Davy* electrochemistry *Dalton* atomic theory *Avogadro's* hypothesis			
Oersted electromagnetism *Ampère* *Ohm* *Carnot* motive power of heat	*Berzelius* organic analysis		*Cuvier* palaeontology *Lamarck* adaptive evolution *Amici* achromatic microscope	*W. Smith* stratigraphy
Gauss *Faraday*	*Graham* law of gas diffusion *Liebig* organic chemistry		*Baer* cell theory *Schlieden* *Schwann*	*Lyell* uniformitarianism
Mayer, Joule, Helmholtz, mechanical equivalent of heat *Kelvin* dynamic equivalent of heat *Maxwell* electromagnetic theory of light *Cannizzaro* Avogadro's law	*Frankland* organo-metallic chemistry *Clausius* kinetic theory of gases *Pasteur* structure of organic molecules *Berthelot* thermochemistry *Kekulé* valency, benzene ring *Mendeleev* periodic table		*Darwin* 'Origin of Species' *Pasteur* germ theory *Mendel* laws of heredity	
Wilde dynamo *Hertz* radio waves *Rontgen* X-rays *Millikan* charge of electron	*Van't Hoff* stereo chemistry, thermodynamics *Ostwald* thermodynamics *Le Chatelier* chemical equilibrium		*Bateson, De Vries* rediscovery of Mendel's laws	
Lorentz electron *Becquerel* radio activity *Thomson* mass of electron *Planck* thermodynamics *Soddy* isotopes *Rutherford, Bohr* nuclear atom *Moseley* X-ray spectra *De Broglie, Heisenberg, Schroedinger,* wave mechanics *Einstein* general relativity	*Curie* radium	*Buchner* enzymes	*Pavlov* conditioned reflex *Hopkins* vitamins *Banting* insulin *Fleming* penecillin	continental drift
Hahn nuclear fission electron microscope electronic computers radio astronomy cybernetics		*Warburg* respiratory enzymes *Krebs* biological cycle *Lipmann* ATP	*Haldane* hypothesis on the origin of life	
maser laser		*Tatum, Beadle* biochemistry of heredity	*Lysenko* genetic controversy in Russia *Huxley* muscular contraction *Watson, Crick* genetic code *Eccles, Hodgkin* nerve conduction exobiology	plate tectonics
quarks 300-1000 GeV machines integration of physics and cosmology	chemical structures and properties by computer	synthesis of genes rational pharmacology	understanding of brain mechanisms developmental biology ecological interactions with environment	

first time, it became possible to know their quantitative composition: x per cent of carbon, y per cent of hydrogen, and so on. But this information by itself was useless for two reasons. First, to know how many atoms of carbon, hydrogen and so on might be present one had to have access to atomic weights. Only by the middle of the century were the clouds of uncertainty beginning to lift from this area of chemistry. Secondly, it does little good to know that a substance can be represented by the single formula C_6H_{14} since this formula can stand for five different combinations of atoms. In other words, chemistry had to proceed from composition to structure.

The idea that a unique molecular arrangement or structure was associated with each chemical species emerged during the 1850s and 1860s, thanks largely to the work of Kekulé (1829–1896) and Butlerov (1828–1886). And in the course of this development an unexpected regularity was discovered in the concept that came to be known as valency. Kekulé and Frankland are two of the most important names here.

In 1863 leading chemists met at Karlsruhe for a conference on the problems of nomenclature and combining weights. In attendance was an Italian chemist, Cannizzaro (1826–1910), who distributed a paper outlining his system of nomenclature as developed in the course of teaching. It made central use of the old discredited hypothesis of Avogadro (1776–1856) and Ampère (1775–1836) (the one an obscure outsider and the other regarded by his contemporaries as brilliant but frequently unsound) that equal volumes of *all* gases (under 'standard' conditions of temperature and pressure) have equal numbers of molecules. The German Lothar Meyer (1830–1895) read the paper, saw its significance, and the confusions of more than half a century were resolved (Unit 5).

As 'inorganic' chemistry was plunging forward, the sister science of 'organic' chemistry was beginning to hack into its own thicker jungle. Progress here depended on the realization that there are more complex things than atoms, functioning as the 'indivisibles' of a reaction; and that one can have several distinct species of these 'radicals' all with the same proportion of constituents. The organizer of the breakthrough was Liebig (1803–1873), partly through his own researches and partly through his contribution to the social and institutional side of chemistry. Taking up a professorship in 1824 at the obscure German university of Giessen, he proceeded to create a new system of chemical education. There were some precedents for the appreciation of the necessity of practical instruction for students of chemistry; but Liebig was the first to make the laboratory the centre of the system. His students first mastered the standard techniques and the best soon passed on to original work under his supervision. He did more than produce a model for education. By his dynamic personality, he created a band of devoted disciples who carried his approach to chemistry and its teachings all over the world. It was his influence that was to be felt in the reorganization of chemical education in Britain, and the establishment in London of the Royal College of Science, now part of Imperial College. And he incidentally spread his interests beyond laboratory chemistry, to speculative theory, on the one hand, and to agricultural chemistry (with the appealingly simple theory of a phosphorus-potassium-nitrogen cycle between plants and soil), on the other.

The solution of old problems opened the path to new ones. In organic chemistry, there was still a step to be taken in the appreciation of the importance of the three-dimensional structure of molecules. Hints of this were provided by Pasteur's discovery of mirror-image molecules, which he hoped would provide the key to living processes (Units 10, 14). It was, however, a young Dutch lecturer at a veterinary school, van't Hoff (1852–1911), who braved the wrath of leading German chemists, and announced 'chemistry in space'.

The establishment of relative weights of atoms gave a natural *order* to the elements and speculations about regularities in this order proceeded apace. Mendeleev (1834–1907) (Unit 8) and Lothar Meyer developed the 'periodic table', which predicted the properties of hitherto unknown elements. Their existence was soon to be confirmed and the structure of matter in its chemical aspects was established.

On its secured foundations, chemistry could now change from being the servant and adviser of industry to the new role of creator of industries. The lead here was taken by the British, through William Henry Perkin (1838–1907) (Unit 10). While still a teenager, he discovered a reaction which proved the basis for a process whereby synthetic dyestuffs could

be prepared from the chemical derivatives of coal-tar, a nasty sludge formed as a by-product of domestic gas manufacture (the heaps of which helped make the 'gasworks' districts amongst the worst slum districts of nineteenth-century towns). But his was a temporary intrusion into a basically German affair. Perkin's teacher was the German Hofmann (1818–1892), Liebig's pupil and Professor of Chemistry at the Royal College of Science. Although Perkin personally could keep up with the rush of invention that followed, once he retired from his firm the British fell behind, leaving a virtual monopoly to Germany.

Germany's dominance soon extended to all of industrial chemistry. With the *Technische Hochschulen* producing manpower, a patent law drafted for the benefit of the industry, and capital flowing in, the Germans secured a quantitative and qualitative lead which lasted until the First World War (see also H. and S. Rose, *Science and Society*, Chapter 3). The industry also provided unrivalled facilities for research; thus Fritz Haber produced the first synthesis of ammonia from atmospheric nitrogen (Units 10, 34) under extreme conditions of temperature and pressure, in a laboratory provided by a chemical firm. This particular achievement soon had great political consequences for, during the first World War, the Germans could produce nitrates for explosives at home, while the British had first to risk submarine attacks on their ships bringing back nitrates from Chile. Under wartime conditions, the State could not easily ignore the lessons of this experience, and so the British established (1915–1916) a Department of Scientific and Industrial Research (the forerunner of today's Science Research Council) to supplement the hitherto informal, gentlemanly and inexpensive support of science conducted through the Royal Society (*Science and Society*, Chapters 3–6 discusses this in more detail).

5.4 FROM CHEMISTRY TO BIOCHEMISTRY

Let us now come back to the beginning of our period, in the earlier nineteenth century, to trace important developments in one of the biological sciences. Here we will find less connection with industry, but more with medicine, philosophy and the conflict of ideas. We can make the transition from chemistry by recounting some major events in biochemistry. The name is relatively new. It had to be invented when the title 'organic chemistry' remained with a field that became, in fact, the chemistry of the carbon compounds (Unit 10). Nonetheless, its origin pre-dates its name; physicians and chemists in the sixteenth and seventeenth centuries performed experiments in 'iatrochemistry', and on the operation of organisms, which today would be recognized as physiology and biochemistry; Spallanzani (1729–1799) (Unit 14) is a case in point. Mediaeval herbalists were the forerunners of today's pharmacologists, who have the resources of a vast industry behind them. Such advances arose partly in response to the pressure of imposed medical and public health demands, in the nineteenth century. But they also required, on the one hand, the underpinning that only a revolutionized chemistry could provide, and, on the other, the clarification of a variety of philosophical problems about the 'nature of life'.

One bit of folk-history will tell us much about the philosophical context of this field. In 1828, it was claimed that Wöhler (1800–1882) had achieved the synthesis of the organic substance, urea; and in retrospect this was hailed as the foundation of scientific biochemistry (Unit 14) – the demonstration that 'vital forces' need not be invoked in the explanation of living processes. At the time of the claim, Wöhler himself was quite modest about it; for he knew well that the constituents of the reaction were themselves products of reactions in living tissue. But as the discovery receded into the past, it assumed increasing significance in the context of a *philosophical* debate, on 'vitalism' (Unit 16). This debate was as confused as it was passionate, for it meant different things to each participant. At its extremes, it involved not only science but religion. The question was whether the man-machine had any need of an immortal soul to steer it. In more moderate versions, it involved only the basic principles of science: whether causal agencies that were not open to precise experimental investigation could be admitted in scientific explanation. The 'vitalists' have commonly been dismissed as reactionaries; but on their side they had not only the evidence of the failure of science up to then in 'reducing' life to chemistry (Unit 16), but also a strong intuition that the complexity and sublety of living processes require some mystic principles of explanation beyond those that were sufficient for reactions produced in a laboratory.

As a topic for debate, the question of 'what is life?' has varied in popularity but, as a perhaps unanswerable question, it has conditioned the directions of research at crucial points in biochemistry. (Unit 21).

5.5 SCIENCE AND NATURAL HISTORY

At this point, you might perhaps ask why this excursion into the history of science started with mathematics and then worked through physics and chemistry to experimental biology? Perhaps you did not bother asking, for 'everyone knows' that the most abstract and mathematical sciences are the most 'fundamental'. But wait – we have just stated a cliché, a bit of that unquestioned 'common sense' that conditions the way that science is conceived and which then influences the way we teach it and assign prestige and priorities between fields. And like all clichés that seem obvious and eternal, this one has risen, and will decline, in particular historical circumstances. Little is known of the history of such clichés, for historians of science themselves tend to accept the clichés of the world of science around them. But it appears very likely that the dominant *style* of scientific research and, with it, the conception of what science 'really is' are conditioned not only by the choice of problems that seem most challenging at the time but by the social and institutional context of the work of science itself. Laboratory science fits neatly into the constraints of employment in a teaching institution. It can be pursued in brief disconnected intervals through the year; the results of research appear and can be published piecemeal and fairly frequently; and it is also possible to make significant advances after a relatively brief period of initiation. By contrast, the 'field' sciences require long and continuous association with some place in the countryside; major works are generally those of synthesis and take a long time to prepare. Among recent philosophers of science, it has been common to refer to 'natural history' as a preliminary, even pre-scientific, phase of development of a discipline. The 'real thing' comes only when more detailed and basic work in the laboratory becomes possible. It is certainly true that the laboratory approach lends itself more easily to an interaction of particular results with general theories and also to standardized industrial processes. But the recent rise of concern for 'environment' may well bring a criticism of the laboratory approach for the seeming irrelevance of most of its results; and the now-traditional ordering of prestige among the sciences may be reversed. This is not to say that we will turn the clock back; there simply are not enough country gentlemen any more, and the laboratory approach has created powerful tools even for 'natural history', so that mere collections of seashells, butterflies and exotic war-masks will not be re-admitted to the status of scientific investigation except in so far as they contribute to a more general understanding and unifying explanation of aspects of geology, biology and anthropology.

It was during the nineteenth century that the slow conversion of 'natural history' to more laboratory-based sciences began. Central to this change was the development of Darwin's theory of evolution, itself closely involved with a series of philosophical and religious debates that were waged over the issue of the nature of time. It is the relationship of evolutionary theory to the problem of time that explains why we refer to it first here in the section of our history relating to the earth sciences, rather than that relating to biology.

The idea of change and improvement (or deterioration) compared with the past is not at all new; we find it in the Classics; and the term 'modern' was used in what we now call 'the middle ages'. But until very recently, the common conception of 'cosmic' time was either cyclical (the seasons, years, etc.) or dramatic and usually of a short span from start to finish. The Second Coming was due to take place in the year 1000 A.D., for instance (the millenium). The dream of 'restoring' the glories of the classical ages is implicit in the very term 're-naissance'. Any genuine Christian lived in a cosmic drama of usually three acts, with both the beginning (Adam) and the end (the Millenium) capable in principle of being assigned quite precise dates on a calendar organized around the life of Christ. The 'new philosophy' of the seventeenth century introduced a new idea of time, as flowing uniformly and apparently eternally, but this was seen as a question for mathematics; it did not appear to affect the idea of *historical* time.

5.6 THE EARTH SCIENCES

Geology is concerned with time because of its study of the history of the Earth. As we might expect, the first rationalistic speculations of a geological nature can be found among the writings of the Hellenic philosophers, several of whom held opinions about the shape and size of the Earth and were well aware that the surface of the Earth was not static but continually changing. Anaximander, about 500 B.C., believed in the evolution of man from fishes, and Xenophanes inferred from marine fossils found on the land that the distribution of land and sea must have changed dramatically. About the time of Christ, we find that the Roman naturalists and historians Pliny the Elder, Strabo and Seneca were contemplating the significance of volcanoes and minerals but, with the downfall of the western Roman Empire, there followed nearly a thousand years in which many of these ideas were either submerged or forgotten. With the scientific revolution of the seventeenth century, the conception of space expanded radically, but for Christians time was very closely bounded. One may smile now at the dating of the creation made by Archbishop Ussher in the seventeenth century – just 4004 B.C. – but he was taken seriously in his own time; and Isaac Newton himself studied the Biblical prophecies for clues to when time on this Earth would come to an end.

The foundations of modern geology developed in the late eighteenth century and early nineteenth century through interest in rocks and minerals of economic importance. Of considerable influence during this formative period was Abraham Werner (1749–1817), a native of Wehrau, Saxony, whose 'Neptunist' theory held that all rocks originated by precipitation from sea-water. Such a theory was extremely vulnerable to geological field observation, and yet, despite the fact that several European workers discredited the aqueous origin of basalt for instance, the doctrine was taught in some European centres well into the mid-nineteenth century.

James Hutton (1726–1797), lawyer, physician and farmer, contributed profoundly to the demise of Neptunism when in 1785 he formulated the doctrine that *all* past changes on the Earth's surface resulted from the operation of the *same* physical laws that operate today, or, as it is often expressed, 'the present is the key to the past'. This doctrine was championed by Lyell (1830) under the title of the 'Principle of Uniformitarianism' during the first half of the nineteenth century and today forms a corner-stone of the science (See Unit 26).

Uniformitarianism ran into headlong conflict with the Book of Genesis, most probably because the magnitude of the charges postulated by Hutton and Lyell (1767–1849) required an enormous span of geological time. The principle was rejected outright by those who still accepted Archbishop Ussher's date for the Creation, but a small group of scientists accepted Hutton and Lyell's geological events and attempted to fit them into the time scale of biblical chronology. To do this they had to fall back upon 'catastrophic' explanations of Earth history (akin to the Biblical Flood), which had already been proposed in 1812 by Cuvier (1769–1832) in his theory of Catastrophism based upon his discovery of fossil extinctions in the Paris Basin. As much more geological data was collected, Catastrophism waned in the wake of William Smith's recognition of the chronological significance of fossils which is expressed in the 'Principle of Faunal Succession' (see Unit 26). This principle was the key with which to open the history of the Earth and also prepared the groundwork for Darwin's theory of Evolution (1859).

Evolutionary theory, like uniformitarianism before it, did not receive the immediate recognition it might have done because of the small amount of geological time that seemed to be available, according to the then best estimates. It was not until the development of modern radioactive dating methods (Unit 2) that adequate evidence for an age of 4,000 to 5,000 million years could be obtained.

Undoubtedly one of the most exciting periods in the history of the Earth sciences began in 1960 and may be regarded as a scientific revolution (see the preface of the Open University Earth Science Reader, *Understanding the Earth*). This was due in large measure to the development of oceanographic geophysics which has led to the general acceptance of the theory that continents have drifted about the face of the Earth. Recently, geological and geophysical

data have been fused into an all-embracing theory of plate tectonics, which not only explains what has happened in the past but also what is likely to happen in the future.

The Earth sciences have been, and are likely to remain, essentially historical. Nevertheless, the exact methods of physics and chemistry are increasingly used and the precision and rigour of mathematics commonly employed. Like the physical sciences, the Earth sciences have the precision to predict, but this usually involves prediction in space rather than time.

5.7 BIOLOGY

The study of living forms had its own separate history. In the eighteenth century, the Swede Linnaeus (1707–1778) made the first successful classification of plants, based on the properties of flowers' reproductive organs. Although his scheme was later modified, the importance for subsequent systematic biology of Linnaean classification remains. The nomenclature for species which Linnaeus introduced is still used (Units 19, 20, 21). It formed the basis for Darwin's later work. Occasional speculations about whether and how new species might have arisen since the first creation gave way to the coherent (if also speculative) theory of Lamarck (1744–1829) (Unit 19). It was that parents can transmit to their offspring some of the bodily modifications that they have achieved through adapting to their environment during their own lifetime. But such a theory could only be used to explain particular phenomena; it was not of great relevance to the major theoretical problem in classificatory natural history: the definition of a species.

The reason why evolutionary theory emerged in Britain in the way it did owes something to the development, towards the middle of the nineteenth century, of a major debate on the reconciliation of the evidence of natural history and geology with the text of the Bible, with which it was felt to be increasingly at variance. In addition, however, there was a strong 'natural history' tradition in Britain, perhaps related to the existence of an independent 'squirearchy', a leisured class with its roots in the land but whose members did not own the type of vast estate of many continental aristocrats. This tradition of the observation of nature was both symbolized and helped to develop by the publication of such books as Gilbert White's *The Natural History of Selborne* (1789), a record of many years patient observation of a small corner of rural England. The experience of agriculturalists in their breeding of domestic species of plants and animals also played its part (Units 19, 21).

The work of Charles Darwin was thus assured of a wide audience. He adopted Lyell's principle of trying to explain natural phenomena naturalistically, and also in terms of present agencies. Then the idea of 'survival of the fittest' came to him, directly inspired by the *Essay on Population* of the Rev. Thomas Malthus (1766–1834), in which the latter argued that 'moral restraint' among the poor was the only humane way of preventing massive population growth, overcrowding, famine and disaster. Darwin spent many years in touching up the arguments for his theory, sharing the secret only with a few friends; for he knew that it would arouse strong opposition. It was only when he received a letter from Alfred Russell Wallace (1823–1910), a free-lance explorer and specimen-collector, describing conclusions identical to his own, that Darwin dared to publish.

His great book, *On the Origin of Species*, was a sensation. But oddly enough, all the evidence he provided for his theory was indirect: the evolution of *varieties*, partly induced from observation of nature, and more firmly established by the study of the breeding of domesticated animals. The palaeontological record at that time had too many gaps and discontinuities to be useful, although in later years several series of 'missing links' were constructed, not all of them accurate. On the question of the mechanism of transmission of properties from parent to offspring, Darwin was neither clear nor confident. But with his mass of evidence and his candid admission of unsolved problems, he pointed the way to a major conceptual clarification of the biological problems of the relationship between species and their emergence.

Darwin's subsequent work, *The Descent of Man*, produced an even more violent reaction, for here the evidence was used to show a history of man extending back for many thousands of years, and merging into that of non-human creatures. The British Association had its greatest moment in 1860 when Thomas Huxley (1825–1895) debated for Darwin against

Bishop Samuel Wilberforce and quietly demolished him. Why there should have been so much fuss in England alone can partly be explained in terms of the peculiar state of the Established Church at the time – under political attack for clinging to its traditional wealth and privileges and also troubled by the loss of some of its leading intellectuals to Roman Catholicism.

So 'Darwinism' was in England, and to some extent elsewhere, the slogan of the revolt of the youthful intellectuals of the age. For them, in battle with their conservative elders, it seemed that the world was being transformed. The old religious certainties needed re-evaluation. Mankind seemed to be on its own, as a species different from others and yet recognizably related. And for the history and fate of mankind, the answer was to be found in Evolution, up from the primaeval slime to the great conquest (over nature and man) of optimistic Victorian civilization.

Once launched on society, 'Darwinism' took on a life of its own. For example, the justification of the brutalities of nineteenth-century industrial society on the basis of the 'naturalness' of the struggle for existence and the survival of the fittest (a sophisticated version of 'might is right') was labelled 'Social Darwinism' by its adherents. At the same time, Darwinism made an immense impression on socialist theorists such as Karl Marx (1818–1883). Marx wanted to dedicate one of the volumes of *Das Kapital* to Darwin who, however, declined the honour. Christian Darwinists reconciled their support for evolution on the grounds that, if there was selection, must there not also be a Selector?

The intimate involvement of Darwinist biology with the social and philosophical questions of the time was matched, too, by the steady advance in 'reductionist' biology (Unit 16) over the century. Some account of this is given in the radio programme of Unit 14. The key themes were the development of a biochemistry of the *substances* present in living systems and a microscopy enabling an interpretation of the *structure* of living systems. Cell theory was one product of this analysis. Biochemistry and cell theory together combined to influence another major nineteenth-century debate, that on spontaneous generation. Early biologists were very uncertain as to whether life could in fact arise spontaneously and, whilst by the mid-nineteenth century no one would argue that this could be true for larger animals like rats or flies, a whole new area of uncertainty surrounded the world of minute creatures revealed by the microscope. Perhaps bacteria could indeed arise from non-living substances. Darwin himself did not discount the possibility, and *some* explanation for the origin of life was necessary if one was not to accept that life was independent of the non-living science of chemistry and physics. Thus a confused picture, in which the protagonists of a 'rational' biology lined up alongside the 'spontaneous generationists' emerged. It was Pasteur (1822–1895) in France, while investigating the severely practical problems of diminishing the losses caused to the French wine industry by microbial contamination, who produced the most rigorous (although still contested) demonstration that microbes could not develop in organic broths if adequate precautions to destroy them and prevent their re-entry were taken before the broths were incubated. Indeed, his name is still recalled in the process by which one such class of infection is prevented – Pasteurization in milk.

Pasteur's experiments provided the experimental rationale for 'germ-theory'. 'Life begets life' was one of its major theoretical conclusions, presenting problems for interpreting the *evolution* of life that are only today beginning to be resolved (Unit 21). One of the major practical consequences of germ theory, though, was to underpin the expansion of medical and public health facilities that the nineteenth century saw. The development of vaccination by Jenner, (1798) originally for smallpox, and of antiseptic techniques by Lister (1827–1912), began the conversion of medicine from the mixture of shambles and art form which it had been up till the end of the eighteenth century, before ever germ-theory and the nature of infection were apparent. Florence Nightingale (1820–1910) designed hospitals which minimized cross-infection of patients and dramatically reduced death rates, based on her practical experience of the horrors of the Crimean war, where the risk of dying in hospital was much greater than if one was left to recover outside. Edwin Chadwick (1800–1895) began the reform of the British sewage and fresh-water system that was to minimize the chances of urban epidemics

and make the massive outbreak of communicable bacteria-borne diseases* a thing of the past in the industrialized world, in a similar theory-free way. The great epidemics that had scourged mankind for all history came to an end with improved sanitation and nutrition in the cities. But theory and practice were to unite only in the present century in the long search for a 'magic bullet', a substance which killed bacteria whilst leaving the host organism unaffected. This search, hastened by the deaths from infection in two world wars, culminated in the discovery, and later the manufacture, of penicillin in the 1940s. The period since then has been perhaps as much the antibiotic age as the atomic age.

Darwin had to do without the laboratory biology of germ and cell theories. His work was a *description* of a process, rather than its *explanation*. The *explanation* depended on the rediscovery of Mendel's work and the revival of genetics at the end of the nineteenth century. (Units 17, 19). The development of the idea of particulate inheritance and the apparent refutation of Lamarckism owes much to Morgan (1866–1945) and to the development of statistical methods for studying the genetic behaviour of populations by Fisher (1865–1940) and Haldane (1892–1964) in Britain in the 1920s and 1930s. The experiments of the early geneticists did not, however, provide an *explanation* in chemical terms of the mechanism of inheritance, replication and mutation. This had to wait until the molecular biology of the 1950s onwards, a historical development in the reverse order to the presentation used in Units 17 and 19.

The involvement of genetics with social and political controversy did not end with Darwin and the early twentieth-century geneticists. A combination of Malthusianism, Darwinism and genetics led to the development of a so called science of 'eugenics', advocating genetic regulation so as to improve human stock in parallel with that of domestic plants and animals. By the time of the great depression of the 1930s, some advocates of eugenics were advising the British government to sterilize the poor, in particular women whose husbands were on the dole. The advice was rejected in Britain but a comparable policy was enthusiastically developed in Nazi Germany. Most adherents of eugenics changed their minds at this point but, if one reads 'the Blacks' for 'the poor', one can see the ancestry of some debates now current. At the same time, a determined effort to challenge the prevailing view of genetics as established by Mendel and Morgan led, through the 1930s, 40s, and 50s, to the extraordinary conflict within the Soviet Union between the essentially Lamarckian Lysenko and his orthodox geneticist opponents, such as the plant geneticist Vavilov, who died, disgraced and in exile, in 1941. Official approval for the Lysenko 'line', was given by Stalin himself. The bitter dispute in Soviet science over what constituted a 'socialist biology' continued until the 1950s and did much to impoverish biology in the Soviet Union.

5.8 A PAUSE FOR PERSPECTIVE

Up to this point, we have been considering the period of science history that extends nearly continuously up to the present. The industrialization of science and the activity and achievements of academic science are part of the 'science' that in one way or another is alive and relevant today. Indeed, without a knowledge of this 'immediate past' the present cannot be understood. The ideology of 'academic science' had sheltered several generations of scientists from the problems of involvement in industry and society and so left them unprepared for today's new situation of science (to which we return in Units 33 and 34). A knowledge of the complicated paths of development of different areas of science not only relates the hard facts to very lively humans; it can help to identify real difficulties and obscurities in the material of the Course, such as the problem of the alternative views of light as waves and particles (Unit 29), or of the relationship between Einstein's and Newton's interpretations of motion (Units 3 and 4).

The more remote past is, by definition, less relevant to the present. If you are curious about the earlier roots of modern science or about the great variety of ways in which men have conceived and undertaken the study of the natural world, the earlier history of science can

***Diseases such as influenza are caused by viruses and even today not so readily controllable, as most of us know to our cost.**

be interesting and important for you. But in this brief essay we will content ourselves with a rapid survey of what happened before the nineteenth century. You can read more of this period in the background reading book *Science in History*, and you will have the opportunity to take courses in the History of Science later at the Open University.

6. THE ORGANIZATION OF SCIENTIFIC WORK: THE FRENCH REVOLUTION

We have already seen how the Germans followed a French example in science and scientific education. For the social aspects of science, as for so many other things, the French Revolution can be taken as the start of the contemporary world. For, during and following that Revolution, there appeared institutions for *recruitment* through scholarships for talented boys, *jobs* in part-time teaching and examining, *State support* for basic science and *systematic applications* of science and the scientific approach to war and industry. The centre of the system was the École Polytechnique of Paris, mainly serving to train army engineers; but the greatest scientists taught there, and there they found their most promising students.

This did not happen by accident. The French Revolution was a new sort of revolution, committed to the abolition of privilege based on birth; and France was fighting in a new sort of war, in which the whole population was involved. The combination of idealism and need gave an impulse to the growth and utilization of science. Its special form was set by several traditions in French intellectual life. The most important of these was the historical period of the eighteenth century known as the 'Enlightenment', in which the approach to natural science, developed during the 'scientific revolution' of the seventeenth century, was extended to the analysis and criticism of society. In this movement, there was a strong faith in *mathematics*, both as a way of thinking and as a powerful tool. In addition, the French response to the early *industrial revolution* had, as in other continental countries, led to the establishment and improvement of colleges for the training of engineers. These provided the possibility of job opportunities which were to be greatly expanded during and after the Revolution. They also established a tradition of higher education. With this background, it is not surprising that the early efforts of French scientists during the Revolution were devoted to rationalizing existing systems and applying mathematics to them as much as possible. This approach can be seen in new systems of chemical nomenclature (such as that proposed by Lavoisier) and also in the 'metric' system which tried to unify all measures on a natural foundation, using the scale of ten.

At the time of the Revolution, France already had a group of eminent scientists (the astronomer Laplace, the chemist Lavoisier, the mathematician Monge and many others). They all participated in the teaching and application of science and shared in the work and the hazards of revolutionary life. Under Napoleon, those who had survived, organized a programme of teaching, research and application of science that was the envy of the world and, for thirty years, Paris was the centre of the scientific world. But this glory did not last indefinitely; by the 1820s, stagnation was setting in. One sign of this was the exclusion, partly for political reasons, from the scientific community of two men, who, although they died young, left work which transformed their fields: Sadi Carnot in thermodynamics and Evariste Galois in algebra (see 5.1, 5.2).

Even during the formative period of French revolutionary science, there was an incident that can remind us of the limits of the sort of science that was shaped by those events. The mathematical sciences were restricted to those few who had the opportunity for formal education in their youth. They were a foreign language to the great majority of craftsmen and artisans. During the early revolutionary period, this association of science with a social élite was perceived and resented. Inventors who could not give a scientific explanation of their devices to the Academy of Sciences' commission on inventions were ridiculed and dismissed. Lavoisier's attempt to reform chemical nomenclature seemed to be a plot to take

chemistry away from the self-educated craftsmen by making its language incomprehensible to them. During the most radical period of the Revolution, the Academy of Sciences was shut down while the more populist Museum of Natural History flourished; and this ideological struggle may have been one of the factors which led the French Revolutionary government to execute Lavoisier. With the decline of the Revolution after 1794, French science returned to its mathematical bias. It was then that the École Polytechnique was established. But the tensions between élite scientists and the non-scientific citizenry revealed by that episode cannot be said to have been solved even today. Indeed, some would argue that they are now more acute than ever.

7. THE 'ROMANTIC REACTION' AND SCIENCE

Roughly contemporary with the French Revolution, there occurred an episode in the history of science that later scientists and historians have usually regarded as an unfortunate aberration. In Germany, around the beginning of the nineteenth century, there flourished a strange, exotic growth called 'Naturphilosophie'. Its devotees, led by the great poet Goethe and the philosopher Schelling, denounced the dry, soulless mathematical and experimental science of the eighteenth century. Instead, they proposed a 'philosophy of nature' in which hand and eye, mind and spirit would all be united. Goethe led the way with an (unsuccessful) attack on Newton's theory of colours and with his attempt to find an organizing and unifying principle behind the structure of all the vertebrates. His followers imbibed the atmosphere of enthusiastic philosophical speculation in Germany in the opening years of the nineteenth century and attempted grand speculative syntheses of all the world, physical and spiritual.

In England this movement had strong effects, if not on science then at least on poetry. Coleridge had studied *Naturphilosophie* and shared his vision with Wordsworth. The romantic utopian, William Blake, probably drawing on the same earlier mystical sources as *Naturphilosophie*, dismissed 'The Atoms of Democritus and Newton's Particles of Light' as part of the blind and dehumanized culture of his age.

The scientific achievements of the proclaimed adherents of *Naturphilosophie* are few, although more may come to light when a more sympathetic history comes to be written. For example, Oersted's work on electromagnetism (1820) was the outcome of a search, conducted over many years, for effects which would display the fundamental unity of the forces of nature. The common pattern was for a young man to be captured by the vision of such a unified science while at university and then spend his life trying to rescue as much of it as possible by heroic endeavours of research.

Eventually *Naturphilosophie* suffered the worst fate of any poetic, romantic movement: it became an orthodoxy, taught by university professors. When the founders of experimental science in Germany tried to gain an entry into the universities in the 1830s, they found the way blocked by the professors of *Naturphilosophie* and there ensued a bitter struggle at all levels, from academic politics to philosophical debate. The scientists eventually won, but for generations they were haunted by the ghost of *Naturphilosophie* and so they curbed the speculative tendencies in themselves and their students most severely, thereby reinforcing the style of objective, academic and inhuman science that the poets had found abhorrent. (Recall the description, in the radio programme of Unit 1, of this sort of science bearing as much relation to the scientific paper as the love affair to the marriage certificate!)

Although the particular style of *Naturphilosophie* was very much conditioned by its location in Germany, the tendency to yearn for wholeness and immediacy in contact with nature recurs again and again. Its present form may be seen in a tendency amongst many to reject the supposed 'aridity' of objective laboratory science in favour of a more subjective, romantic concern for the world. Academic science impoverishes itself if it merely rejects this tendency with contempt.

8. THE CONSOLIDATION OF SCIENCE: THE INDUSTRIAL REVOLUTION

If we look at the scientific scene a mere two centuries ago, we find a very different picture from the present one: hardly any schools, hardly any jobs, hardly any organized support for research and, naturally, very few men engaged in scientific research. Yet there were developments already under way which laid the basis for the great strides in science and its social organization made during the nineteenth century. About two hundred years ago, there began the profound transformation of European economy and society which is known as the 'Industrial Revolution'. It was a gradual process, a combination of many factors. In England in particular, agriculture was being made steadily more productive, and certain manufacturing industries, principally textiles, were expanding rapidly. Population was increasing, and although 'the poor', rural and urban, were becoming a frightening social problem, there were many hands available for the new mills which were created for concentrated, rationalized, cheap production.

Most of the changes in production were accomplished by rationalizing craft techniques or introducing simple machines to replace human arms. But there were critical points in the productive system where 'science' – either elementary physics or chemistry – could effectively solve problems. These were mainly in power engineering and in industrial chemistry. In both these fields, there was a body of materials sufficiently developed for successful application; in the first from textbooks of theoretical and practical mechanics written by followers of Newton; and in the second from the system of chemistry developed by the great Dutch medical teacher, Boerhaave (1668–1738). Thus, although the start of the Industrial Revolution owed relatively little to science, its successive phases, in which industry itself was transformed, depended very strongly on existing scientific knowledge and a small group of experts in its application.

The contribution of the Industrial Revolution to science was similarly indirect, though in its cumulative effects it was decisive for the change from amateur 'natural history' to scientific research. It created opportunities for several sorts of people to pursue science in connection with their careers. The physicians and teachers of medicine were supplemented by engineers, inventors and 'philosopher-manufacturers' such as Josiah Wedgwood (1730–1795), the china manufacturer. These formed the nucleus of an audience for scientific results, so that by the end of the eighteenth century in Britain there was a viable market for several independent journals of science publishing specialized research. These contributed to the further diffusion and expansion of science and also provided a business for their publishers. We have noticed that on the Continent there developed a movement for higher technical education; but in England this made much less progress. Indeed, the 'gentelmen's club' atmosphere of the Royal Society persisted unchanged right up to the 1830s (see also Chapter 2 of *Science and Society*).

These differences in response to the challenge of the Industrial Revolution produced differences in national styles of science which were strong through the nineteenth century, and which leave traces even to this day. German science was assimilated to academic scholarship and its technology was developed from a rigorous intellectual approach. French science remained concentrated in the high-prestige institutions of Paris, themselves financed directly by the State rather than associated with universities. And the British muddled through, relying on gifted amateurs for science, and hardworking craftsmen for industry. In America, science remained 'colonial' and dependent on European stimulus even after political and then economic independence had been won. American pure science became worth noticing, on a broad front, only in the 1920s and its later development would have been much slower were it not for the emigration of refugee scholars from Nazi Germany that took place in the 1930s. Russia, on the other hand, had an excellent, if thin, tradition of scientific work from the eighteenth century and could build on this base after the Russian Revolution of 1917.

9. THE SEVENTEENTH CENTURY: REVOLUTION IN PHILOSOPHY

We have already mentioned two ways in which later developments in science depended on the achievements of the seventeenth century: the Industrial Revolution for its scientific results, and the French Revolution, through the Enlightenment, for its ideology. The significance of 'the scientific revolution' is far greater than these isolated examples indicate; to it we owe the style of investigating nature that has been dominant in science ever since. This includes a careful use of *experience*, caution in *theorizing*, recognition of the need for *co-operative work* and a concern for *application* as well as knowledge for its own sake.

We can appreciate the effects of this revolution by examining the list of sciences and approaches to science that were rejected and discredited by the seventeenth-century revolutionaries. First, there was the traditional higher education, called 'scholastic', which was based on discussion of accepted authors rather than on observations and experiments. Also, there were the ancient 'sciences' of magic, alchemy and astrology. All these depended on the belief in spiritual agencies possessing great powers over the material world. Since the seventeenth century they have all been classed as 'pseudo-sciences'. The 'philosopher's stone' which would convert any metal to gold, the 'elixir of life' which would maintain youth and the 'perpetual motion machine' which would do work at no cost, now seem to be sheer superstition. But because of the view of the world which prevailed almost universally in Europe before the seventeenth century, they were entirely natural and reasonable projects for educated men to work on. The revolution in the way of approaching the natural world was wrought by a handful of prophetic individuals and a small but steadily growing band of followers.

In the early part of the seventeenth century, there appeared works by Francis Bacon, whose profession was law and politics and whose main concern was the social and ethical aspects of science; by René Descartes (1596–1650), who was more philosophical and mathematical, and by Galileo Galilei (1564–1642), who bridged the gaps between natural philosophy, mathematics, and engineering. In spite of the many differences between them, we can see in their pronouncements a common philosophy involving a fundamental recasting of the *objects*, the *methods*, and the *goals* of the study of nature.

The natural world was seen by them as devoid of its magical and human properties: the approach to understanding it must lie in sense-experience and reason rather than in authority or mystical illumination. Accordingly, new methods of investigation were necessary. Strange and prodigious phenomena (such as earthquakes, wonder cures, monstrous births) were seen to be of less importance than regular, ordinary and repeatable observations. The latter were a better basis for establishing the laws of nature. Care and self-discipline were necessary in observation as well as in theorizing; and co-operative work was important for the steady accumulation of knowledge.

The goals of enquiry still had an influence from magic: the ideal of *contemplative wisdom*, the traditional one for philosophy, was replaced by that of *domination over nature* for human benefit. Knowledge was seen as having a purpose relating to life on Earth and not merely as a preparation for the hereafter. But the methods of magic were rejected and ridiculed. The new approach was similar to that of the new type of businessman who calculated monetary profit and loss in a carefully planned venture rather than the earlier feudal nobility who lived in a world of personal obligations and heroic adventures.

A characteristic feature of this new style of work was the recognition of the need for regular, organized co-operation and communication. The Royal Society of London was the first effective and permanent scientific society; and its Secretary published a journal in which results could be announced under conditions which protected the author's property rights in them. In typical English fashion, this was a private club with mainly moral support from the King. On the Continent, the national Academies, like the French, were established by the State, the members gaining an income but losing their independence.

In the framework of the new philosophy, there was a burst of genius in the exploration of nature, culminating in the work of Newton; but like any other revolution, this one did not

make a miraculous change from pure darkness to pure light. Some of the major achievements of science in the early seventeenth century were made by men operating within a conception of nature that was soon to be discarded. Gilbert created the science of magnetism in the course of an attempt to demonstrate that the 'soul of the world' is embodied in the Earth rather than the stars; the astronomer Kepler was forever seeking the 'divine harmonies' in the structure and motions of the solar system; and William Harvey interpreted the motions of the heart and blood as a 'microcosm' of the greater circulations of the living universe. Moreover, outside mechanics and the related branches of physics, the achievements of the scientific revolution were fragmentary and disappointing. A start was made on chemistry, but in biology and medicine there was only a premature attempt at rigour which would not succeed until the nineteenth-century advances in chemistry and physics could lay adequate foundations; and the impact on technology was restricted to the development of vacuum techniques. By the end of the century, the survivors of the heroic period of science realized that the movement was at a low ebb, with few recruits of talent appearing; and not until the quickening of work in the Industrial Revolution was there renewed progress on a broad front.

10. THE REBIRTH OF SCIENCE IN THE RENAISSANCE

These early achievements, which formed the basis of a steadily growing tradition, were the outcome of several developments in different parts of Europe, themselves starting in the fifteenth century. First there was the 'discovery of man and of nature' in the artistic Renaissance of fifteenth-century Italy. The inspiration for this was the rediscovery of Classical antiquity; and the 'humanist' scholars edited and published Latin and Greek texts in all fields, including science. The earliest practical art to be developed and raised in esteem was 'architecture' which included everything from painting to military and civil engineering; the career of Leonardo da Vinci (1542–1519) shows this many-sided activity.

At the same time, the German Alpine region enjoyed a rapid growth in mining, metallurgy and trade. Practical mathematics and the theory and practice of metal-working were developed. A combination of this development with 'humanism' produced the classic *de Re Metallica* (1556) of Agricola (1494–1555), the first comprehensive learned treatise on an industry. Starting in the late fifteenth century, the expansion and conquests of the Spanish and Portuguese fostered a development in all the sciences related to navigation and the conquest and exploitation of resources.

In the sixteenth century itself, the Reformation touched off a series of wars in Europe fought on increasingly 'modern' lines. For these, gentleman officers needed certain mathematical skills and there also grew up new classes of practitioners, such as military surgeons and engineers. The latter provided theories of ballistics and fortification which were as speculative as any twentieth century mathematical theories of war. Nonetheless, by the end of the sixteenth century a standard part of the education of a gentleman was training in some of the mathematical arts. Descartes learned them at his Jesuit school and Galileo taught them to his private pupils. This led to a temporary lowering of the barriers of class snobbery against such arts. Not only men of commerce but also the well-born had contact with craftsmen and practitioners and could appreciate some of their skills. This was of crucial importance for the formation of the goals of the 'new philosophy' and for its acceptance by its educated audience.

Although there was a genuine revolution in the conception of scientific enquiry in the early seventeenth century, the record of successful work in science shows a remarkable continuity with what went before. We have already mentioned Gilbert, Kepler and Harvey; indeed, outside mechanics and its associated sciences, there is little sign of a break. The 'scientific revolution' was thus primarily a revolution in philosophy; both the detailed work in science and the social and technical context developed continuously from the previous century. If we are looking at work in science alone, we can take the 'dawn of modern science' to be the decade of the 1540s. Then, in several fields, there appeared works in which the best

of ancient science was superseded. In astronomy, there was the *de Revolutionibus* (1543) of the Polish Copernicus (1473–1543); this not only announced the heliocentric system of the world but was also a technical masterpiece. In anatomy, there was the *de Fabrica* (1543) of the Belgian Vesalius (1514–1564), creating a new approach to anatomical research and teaching. In mathematics, there was the *Ars Magna* (1545) of the Italian Cardano (1501–1576), in which the solution of the cubic equation was achieved.

Looking back at these steady developments during a turbulent century, we may wonder why the prophets of the 'new philosophy' of the seventeenth century considered the state of the sciences to be so bad. The reason is that the various fields were fragmented and separate and generally they were considered 'arts' rather than 'science'. Attempts at a unified philosophy of nature were made but they were only incomplete, and usually incoherent, speculations. Furthermore, most of this earlier work was done within a conception of nature which was rejected by the 'new philosophy' of the seventeenth century, one in which magic and alchemy were very real and powerful. An extreme example of this radically different approach is found in the work of the Paracelsus (1493–1541) and his followers. He combined elements of magic, alchemy, folk medicine, metallurgical crafts, mystical religion and social and political reform. He called for learning about nature from experience; but it was the experience of the craftsmen, and was to be supplemented and guided by inspiration and scripture. The goals of his science included practical charity for the suffering poor. The Paracelsian tradition of 'romantic' philanthropic populist science was strong through the earlier seventeenth century and, although it later dwindled, the same style of science can be seen in the enemies of Lavoisier in the French Revolution.

II. THE DAWN OF SCIENCE: GREECE

To mark the development of science in the Renaissance, we cited the works in which it first surpassed the achievements of classical antiquity. This is a reminder of how much our modern science is built upon the work of the Greek civilization. Others have made important contributions, to be sure. Our number-system comes from the Indian area through the intermediary of Arabic-speaking scholars. A multitude of practical devices and techniques originated in China. But to the Greeks we owe the intellectual categories in which we organize our knowledge, from basic ideas such as 'cause' to the names and divisions of the sciences. The works of Aristotle (384–322 B.C.) are monuments of empirical investigation of the natural and social worlds; his materials and methods have been used whenever there have been men able to appreciate them. His teacher Plato (428–347 B.C.) showed how reason, independent of sense-experience, could be a valid approach to true knowledge. Mathematics since then has taken its inspiration from him. Both these men owed much to the shadowy figures, called the 'pre-Socratic philosophers', who flourished from 600 B.C. to 400 B.C. They introduced into human thought the idea of understanding the world of sense-experience in its own terms rather than in terms of personified gods; and in their writings we find the philosophical analysis of concepts.

The context of this 'Greek miracle' was that of a civilization on the margin of the great, stable empires of Egypt and Mesopotamia, learning from them but not dominated by them; and as merchants, adventurers and pirates, experiencing the variety of ways of life and of beliefs of the cultures around them. Independence of small communities from central control was their political way of life; and although their world was turbulent and only a few left a mark on history, those few achieved a boldness of intellectual adventure that has never since been equalled. This burst of immortal creativity came to an end with the decline of the independent Greek city-states, about 300 B.C., but their achievements were carried by Alexander the Great all over the then-known world. The Romans were more practical in their concerns and less scientific in their approach to nature. During the long centuries of

the Roman Empire (the first five of the Christian era), almost the only lasting scientific work was done in Greek-speaking areas (Ptolemy of Alexandria, in Egypt; Galen of Pergamon in Asia Minor, on astronomy and medicine respectively, both in the second century A.D.). With the decay of the Mediterranean civilization, such speculative energy as there was concerned itself with religion. And in Western Europe, until the Renaissance, the level of scientific knowledge was low, and of achievement lower still. Fortunately, collections of texts and traditions of learning survived in the Middle East where they were revived by the Islamic conquerors (seventh century onwards). As this civilization was going into decline (thirteenth century), Western Europe was just educated enough to sample its resources and so to re-establish some contact with its classical heritage in science.

12 SUMMARY

We have presented this sketch of the history of science 'looking backwards' so that you could appreciate the relevance of earlier achievements to science today. We have tried to tell the story so that you could see that science has had its periods of greatness and decline, its successes and failures, and its unresolved problems in relating itself to society. The achievements of science, in organizing itself to produce ever greater knowledge and power over nature, have been increasing steadily over the last few centuries. Until very recently, it was natural to suppose that this increase could continue indefinitely, but it is now apparent that new and better controls on science and technology will be necessary if they are to achieve their promise. For this we will require a public which is truly educated in science, both as a system of knowledge and as a social activity. This Foundation Course is designed to help in the creation of a scientifically educated public; and this rapid sketch may help you in attaining your own historical perspective of science.

FURTHER READING

In this essay, we have referred to:

J. D. BERNAL, *Science in History*. Penguin, 1969, 4 volumes.
H. & S. ROSE, *Science and Society*. Penguin, 1970.

Other books that give an interesting general history of science in its connection with society and ideas are:

S. F. MASON, *Main Currents of Scientific Thought: A History of the Sciences.*
F. KLEMM, *A History of Western Technology*, Allen & Unwin, 1959.
Collier Books, 1962.

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